The $K^+ \rightarrow \pi^+ \nu\bar{\nu}$ decay at NA62

PATRIZIA CENCI

INFN, Perugia (Italy)

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Fermi National Accelerator Laboratory
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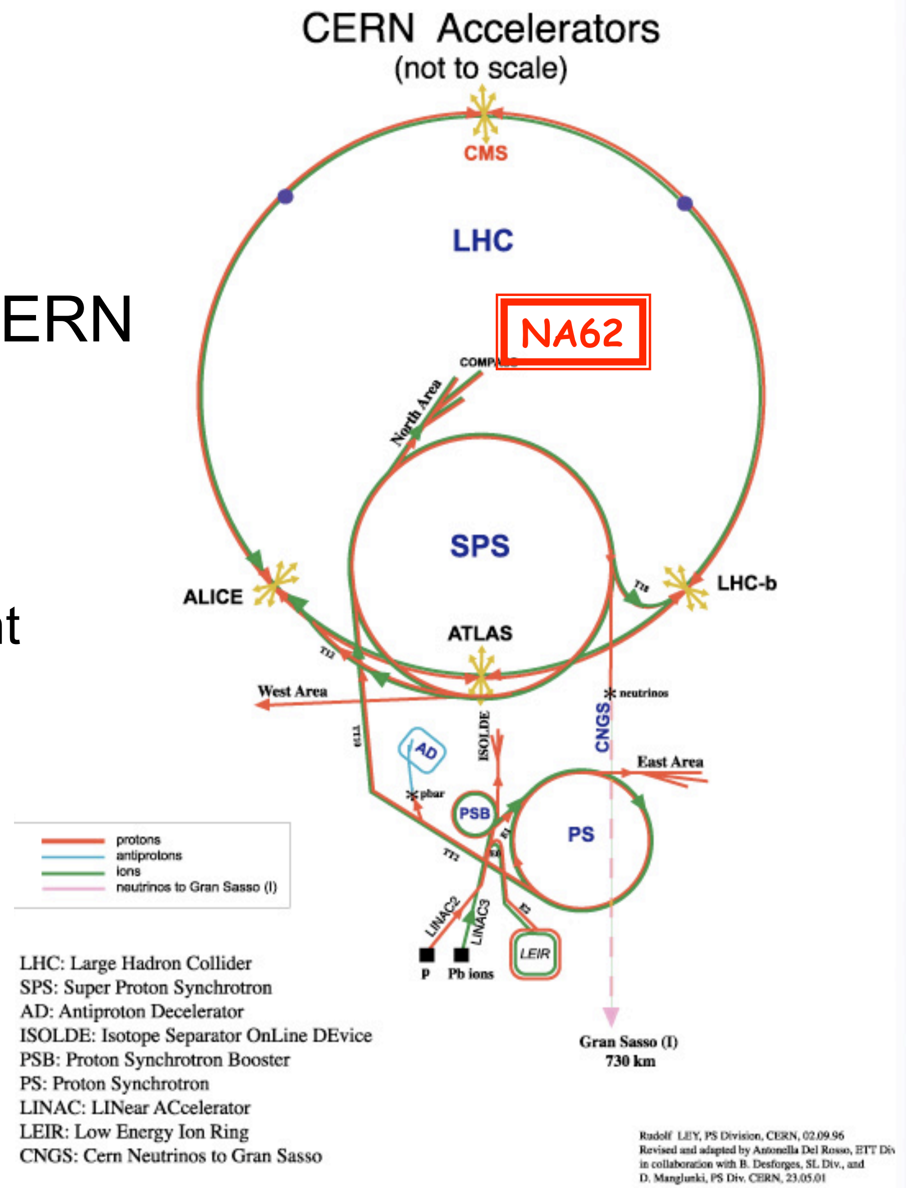
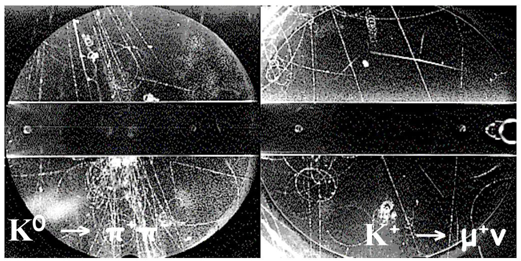
On behalf of the NA62 Collaboration

Outline

- Kaons and New Physics
- The NA62 experiment at CERN
  - Experimental technique
  - Beam and detectors
  - Final $R_K = K_{e2}/K_{\mu 2}$ measurement
- Summary and outlook





The Framework

High energy vs high intensity physics: a positive interplay of direct and indirect New Physics searches

- *LHC: probe the high energy frontier and reveal NP*
  - *direct production and investigation of new phenomena at the TeV energy scale*

- *Rare decays studies at high beam intensity: probe the flavor structure of NP and distinguish among different models*
  - Explore symmetry properties of new phenomena at high mass scales ("1-1000 TeV")
  - Access indirect effects in precision observables
  - State of the art: single event sensitivity toward 10^{-13}

Flavor physics: the golden observables

- Minimal list of key (*or better classes of*) observables

γ from tree ($B \to DK$, ...)	(S)LHCb
$\|V_{ub}\|$ from semi-leptonic B decays	SuperB's
$B_{s,d} \to l^+l^-$	(S)LHCb
CPV in B_s mixing	(S)LHCb
$B \to K^{(*)}\, l^+l^-,\ \nu\nu$	(S)LHCb , SuperB's
$B \to \tau\nu,\ \mu\nu$	SuperB's
$K \to \pi\nu\nu$	Kaon beams (NA62,...)
CPV in charm	(S)LHCb , SuperB's
LFV in charged leptons	Muon beams, (S)LHCb, SuperB's

Gino Isidori

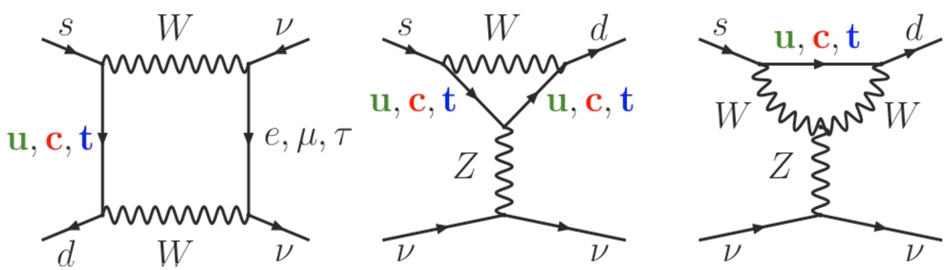
The K → $\pi\nu\bar{\nu}$ decays in the SM

Decay (BR × 10^{10})	Theory (SM Prediction)	Experiments
$K^+ \rightarrow \pi^+ \nu \bar{\nu}$	0.781 ± 0.075 ± 0.029 [1]	1.73 + 1.15 – 1.05 [2]
$K^0 \rightarrow \pi^0 \nu \bar{\nu}$	0.243 ± 0.039 ± 0.006 [1]	< 260 [3]

[1] Brod, Gorbahn, Stamou: PRD83(2011) 034030, arXiv 1009.0947
[2] BNL E787/E949: PRL101 (2008) 191802, arXiv 0808.2459
[3] KEK E391a: PR D81 (2010) 072004, arXiv 0911.4789

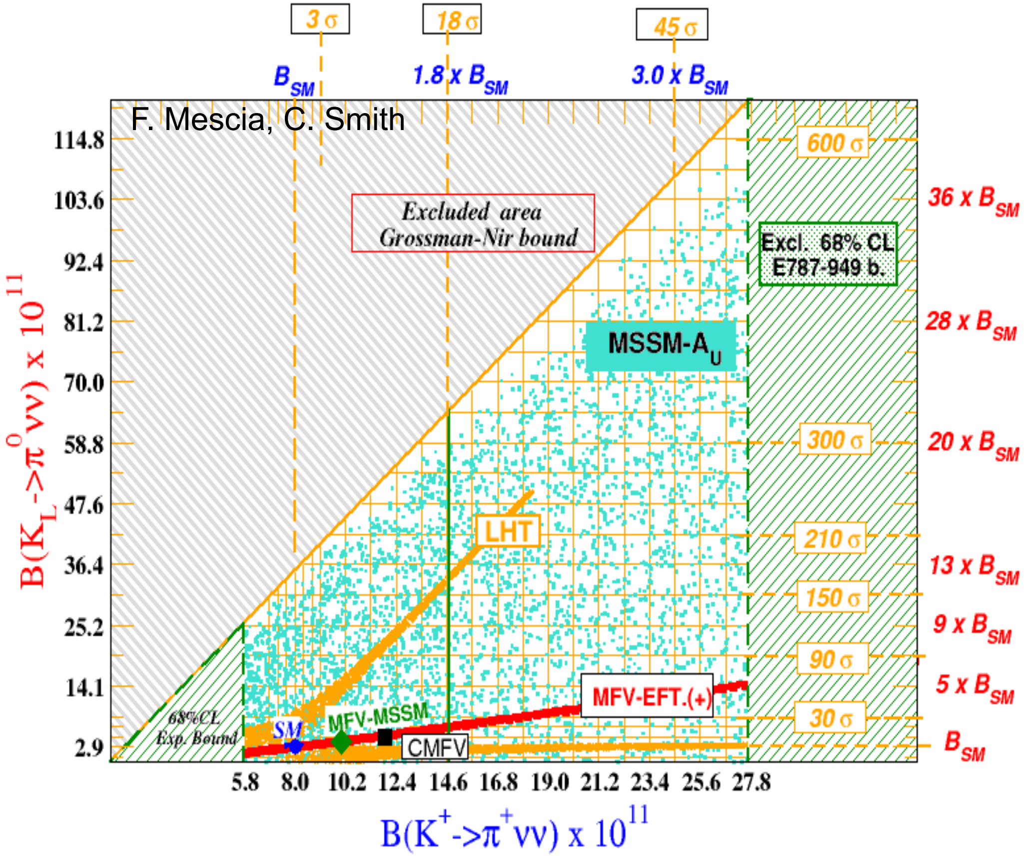
SM predictions are extremely clean

- Short Distance dynamics dominates:
  - FCNC processes only arising at loop level (Z penguins and box diagrams)
- Hadronic matrix element known from K_{e3} semileptonic decays BR via isospin rotation
- Uncertainty dominated by CKM matrix elements
- Amplitude very well predicted:
  - *clean V_{td} dependence*
  - *the BR measurement determines V_{td} without input from Lattice QCD ($\delta BR/BR \approx 10\% \longrightarrow \delta V_{td}/V_{td} \approx 7\%$)*
- Strongly suppressed in SM ($<10^{-10}$):
  - *Key role in seeking NP beyond SM*



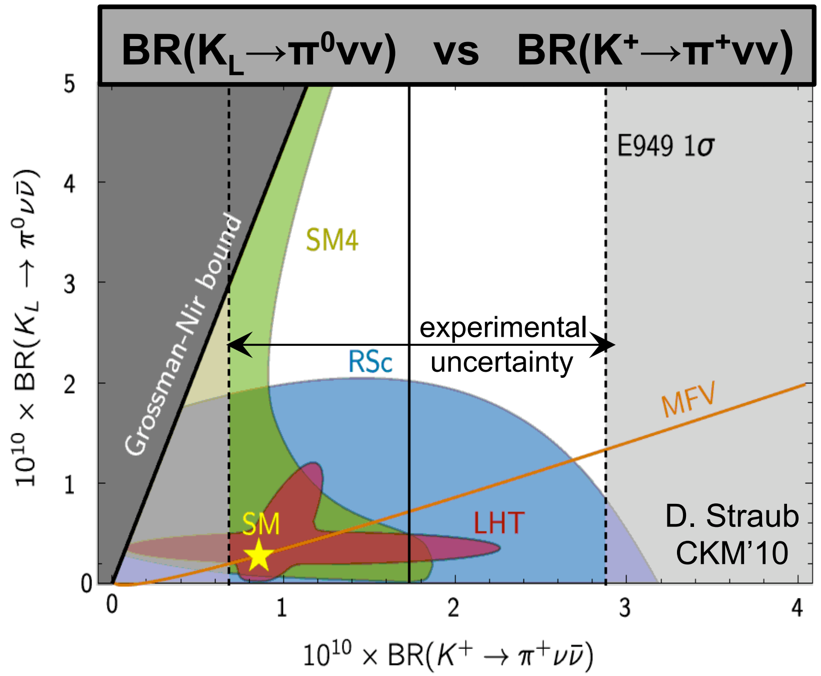
The K → πνν̄ decays beyond SM

- Rare K decays are highly suppressed (CKM) → highly predictive for SM extensions
- Several SM extensions predict sizeable deviations from the BR_{SM} value
- Possibility to distinguish among many different models:
  - *Chargino/H± loops (MSSM at low/large tanβ), R-parity violation (non MFV), enhanced EW Penguins, Little Higgs, extra dimensions, 4th generation, …*



NP models predicting deviations from MFV:

- *Randall-Sudrum,*
- *Littlest Higgs with T-parity,*
- *SM 4th generation*



The NA62 experiment at CERN

The CERN Accelerator Complex

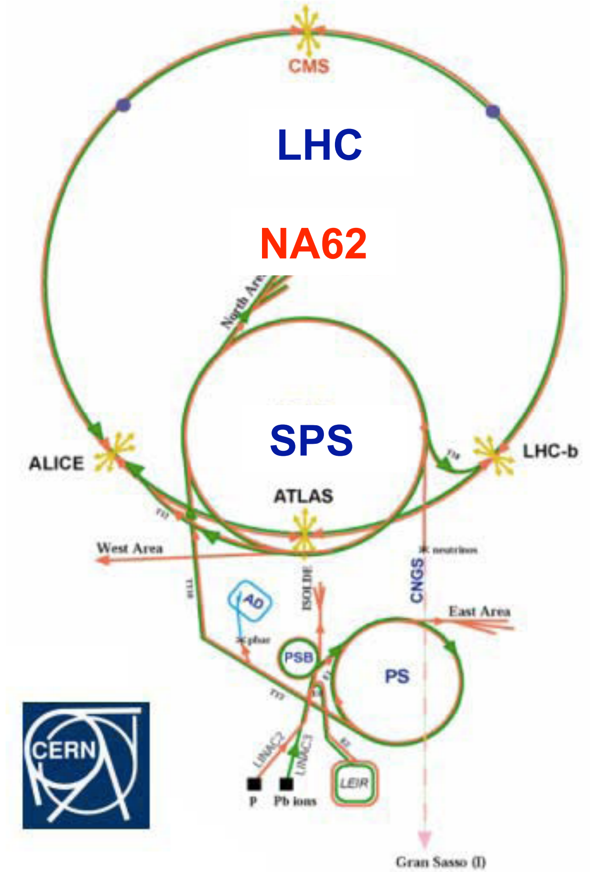
The SPS at CERN:

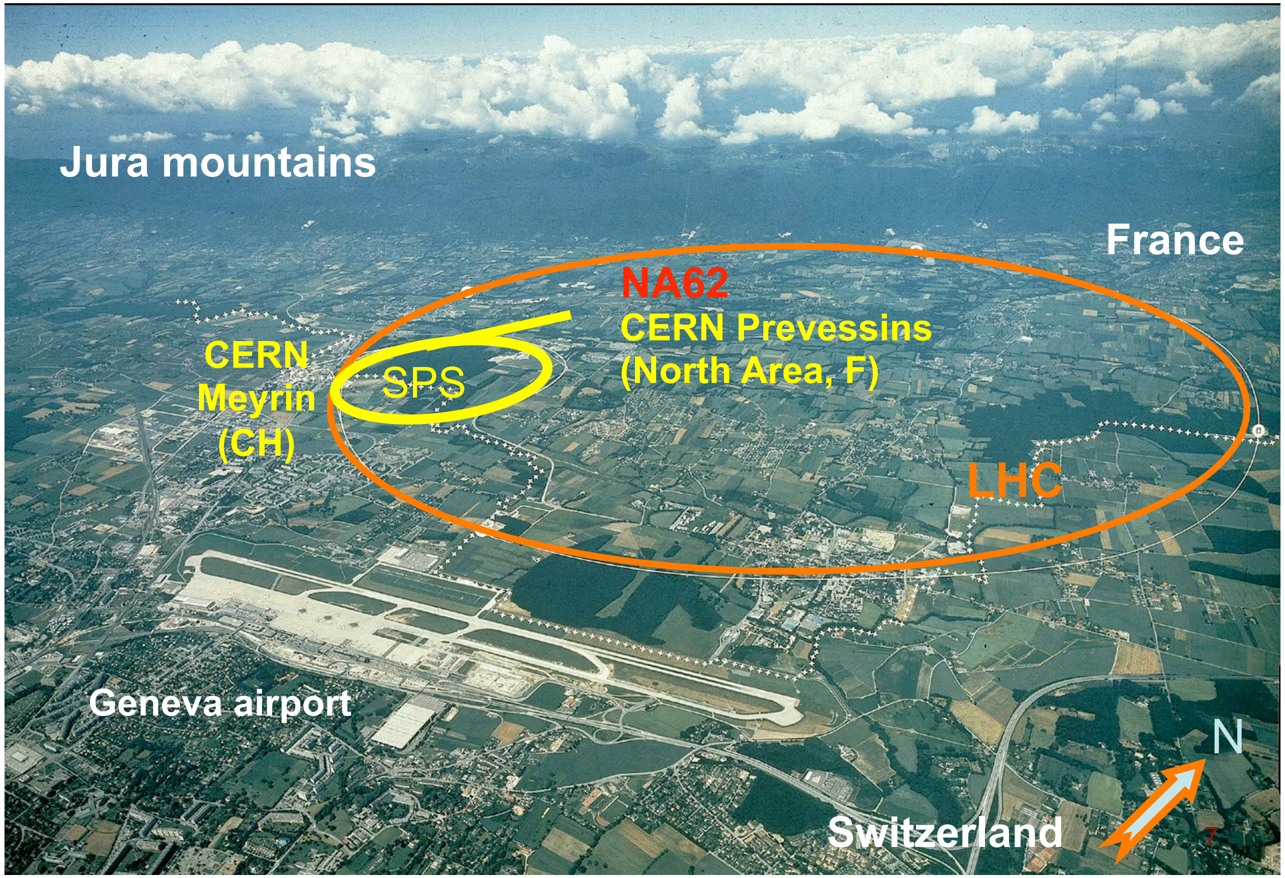
- 400 GeV/c protons
- used as injector for the LHC
- multi-turn fast/slow extraction system

The NA62 experimental program

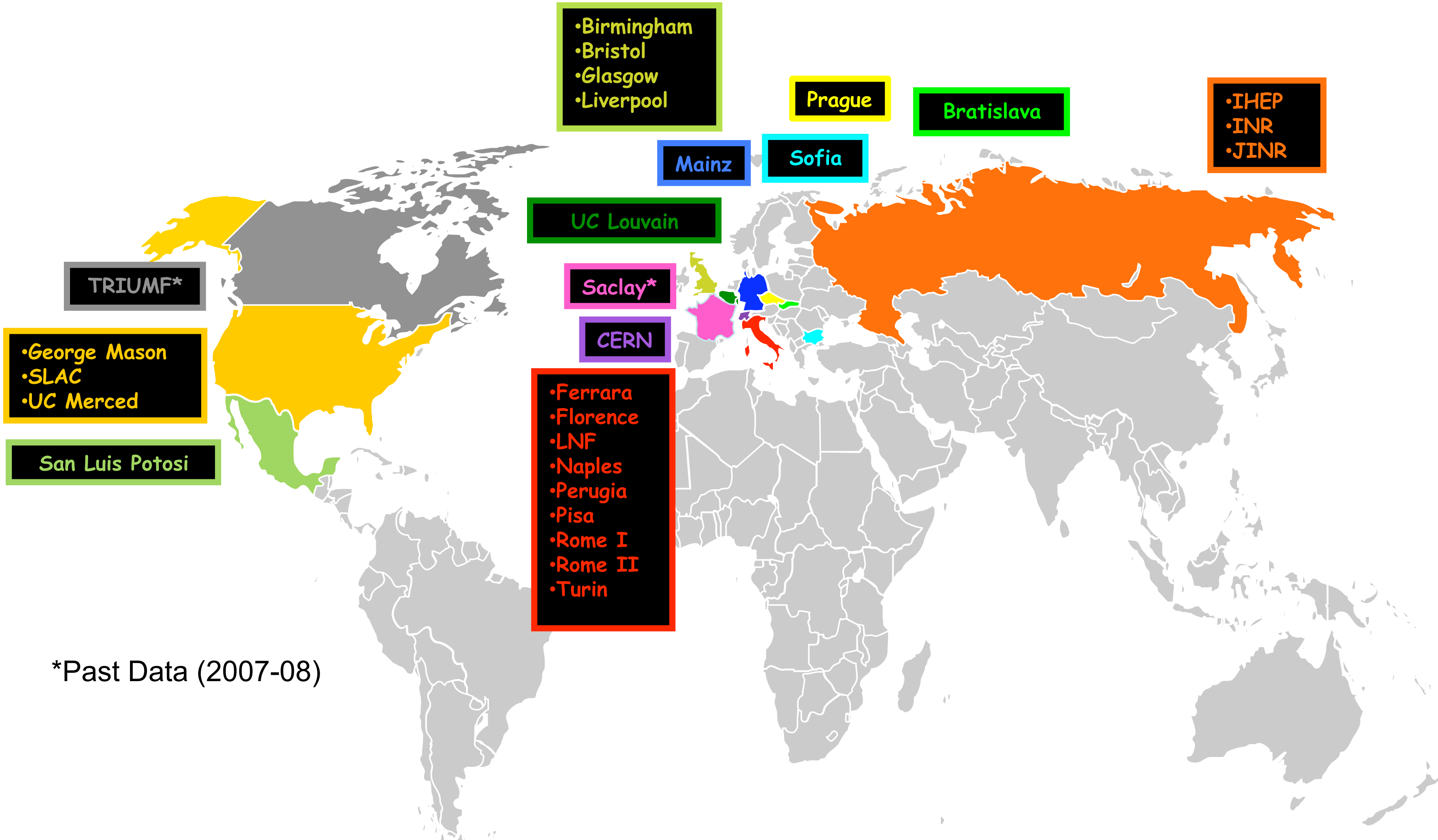
Main goal: measurement of $K^+ \to \pi^+\nu\bar{\nu}$
(O(100) events, S/B≈10; physics runs: 2014-15, commissioning run with partial detector in 2012)

Early stage: measurement of $R_K=\Gamma(K_{e2})/\Gamma(K_{\mu2})$ with precision <1% (physics runs: 2007-08)





The NA62 Collaboration



The NA62 Collaboration: Birmingham, Bratislava, Bristol, CERN, Dubna, Fairfax, Ferrara, Florence, Frascati, Glasgow, Liverpool, Louvain, Mainz, Merced, Moskow, Napoli, Perugia, Pisa, Prague, Protvino, Rome I, Rome II, San Luis Potosí, SLAC, Sofia, Turin

NA62: the experimental technique

Decay-in-flight technique:

Advantages
(wrt decay at rest)

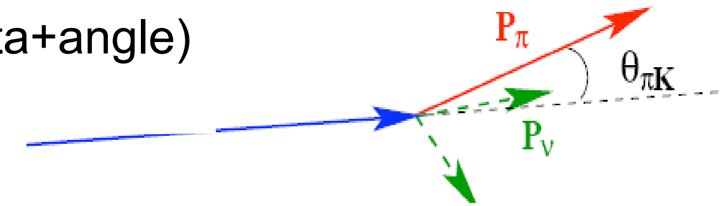
- ➔ easy to have high intensity beam
- ➔ easy to veto high energy photons

Disadvantages

- ➔ long detector and decay region
- ➔ event by event measurement of K momentum
- ➔ unseparated hadron beam

Signal signature:

1 track (momenta+angle)
+ nothing



Background:

All K decays + accidental charged particles
(beam particle interactions)

➔ A challenging experiment with weak signal signature (BR_{SM}=8x10^{-11}) and huge background from kaon decays

Decay	BR
$\mu^+\nu$ ($K_{\mu 2}$)	63.5%
$\pi^+\pi^0$ ($K_{\pi 2}$)	20.7%
$\pi^+\pi^+\pi^-$	5.6%
$\pi^0 e^+\nu$ (K_{e3})	5.1%
$\pi^0\mu^+\nu$ ($K_{\mu 3}$)	3.3%
$\pi^+\pi^0\pi^0$	1.8%
$\mu^+\nu\gamma$ ($K_{\mu 2\gamma}$)	0.62%
$\pi^+\pi^0\gamma$	2.7×10^{-4}
$\pi^+\pi^- e^+\nu$ (K_{e4})	4.1×10^{-5}
$\pi^0\pi^0 e^+\nu$ (K_{e4}^{00})	2.2×10^{-5}
$e^+\nu$ (K_{e2})	1.5×10^{-5}
$\pi^+\pi^-\mu^+\nu$ ($K_{\mu 4}$)	1.4×10^{-5}

NA62: guiding principles

GOAL: 10% precision measurement of BR($K^+ \rightarrow \pi^+ \nu\bar{\nu}$)

⇒ O(100) $K^+ \rightarrow \pi^+ \nu\bar{\nu}$ decays with ~10% background in 2 years data taking

Requirements:

Statistics:

- BR(SM) ~ 8 x 10^{-11}
- Acceptance: 10%
- K decays: ~10^{13}

Kaon intensity, signal efficiency

Systematics:

- ≥10^{12} background rejection
- ~10% precision on background measurement

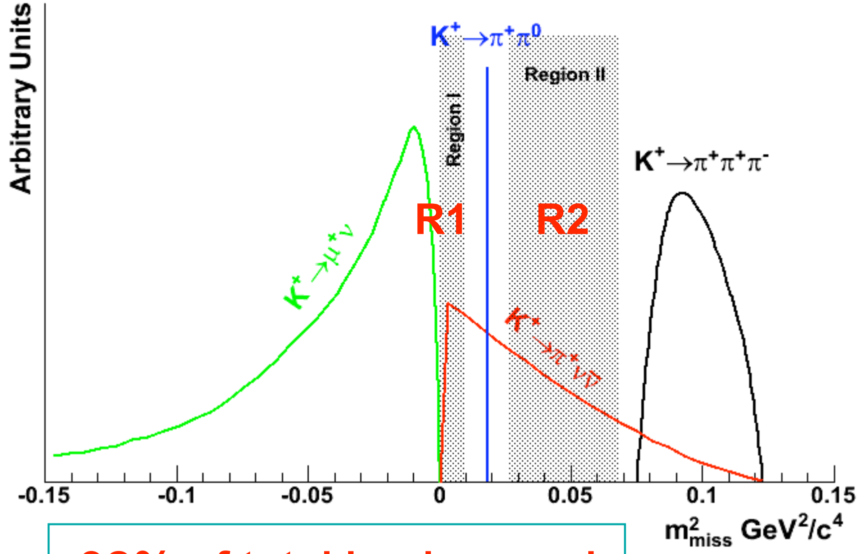
Signal purity, detector redudancy

- → precise high-resolution timing, to support a high-rate environment;
- → kinematic rejection, involving cutting on the square of the missing mass of the observed particles in the decay with respect to the incident kaon vector;
- → particle identification of kaons, pions, muons, electrons and photons;
- → hermetic vetoing of photons out to large angles and of muons within the acceptance;
- → redundancy of information.

NA62: background rejection

$$m^2_{miss} = (P_K - P_\pi)^2 = m_K^2 + m_\pi^2 - 2(E_K E_\pi - p_K p_\pi \cos\theta_{K\pi})$$

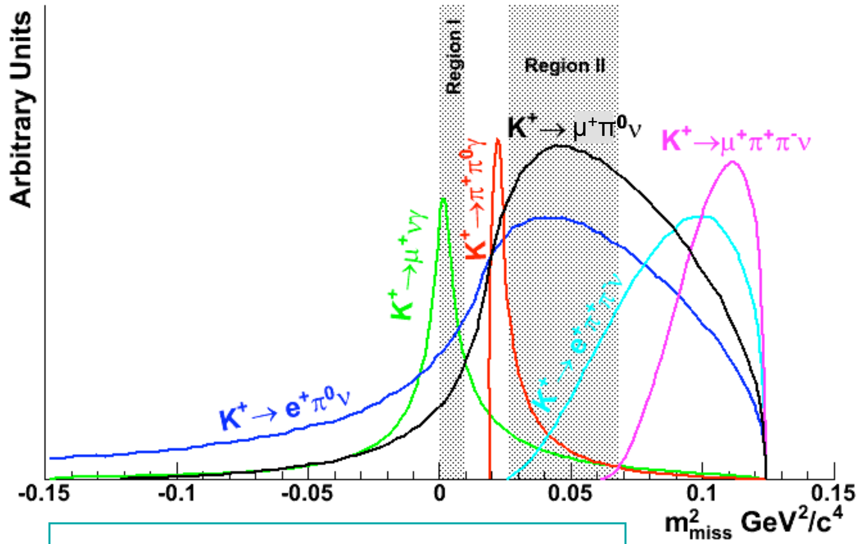
Background separated by kinematic cuts



92% of total background

- Definition of the signal region with low background:
  - ➔ $K^+ \to \pi^+\pi^0$ forces to split it into 2 parts: R1 and R2
- Achievable kinematic rejection power (MC):
  - ➔ ~10^4 ($K^\pm_{2\pi}$), ~10^5 ($K^\pm_{\mu 2}$)
- Rejection relies on high resolution m^2_{miss} reconstruction
  - ➔ low mass/high resolution tracking in vacuum

Background NOT separated by kinematic cuts

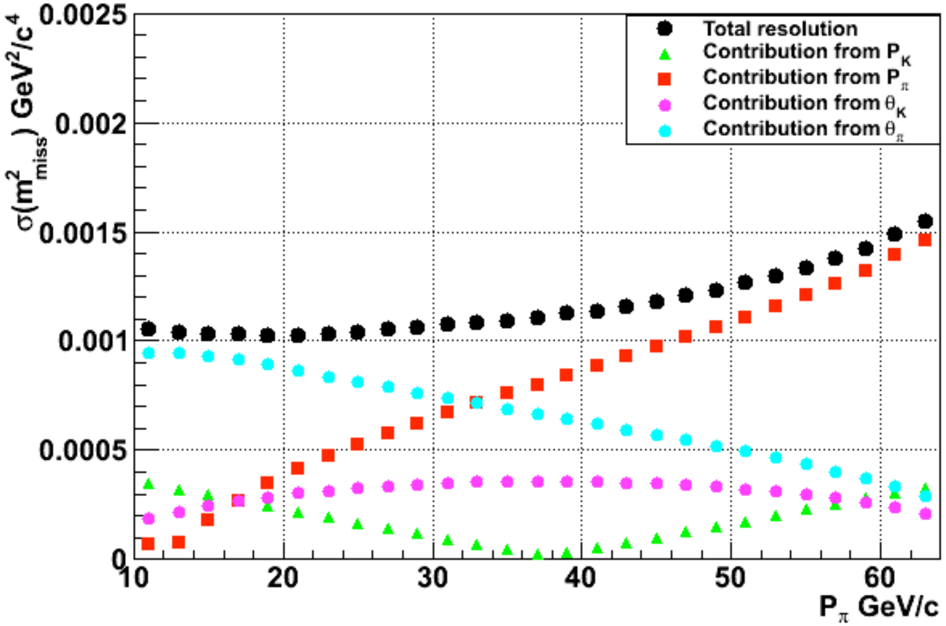


8% of total background

- Radiative decays or ν final states
- Span across the signal region
- Rejection relies on efficient vetoes and PID

The $K^+ \to \pi^+ \nu\bar{\nu}$ Analysis

1. Kinematic rejection
2. Charged particle rejection
3. Photon rejection
4. π/μ separation and μ suppression



Missing Mass Resolution

General Theme: maintain a good signal/background ratio while preserving the signal acceptance as much as possible

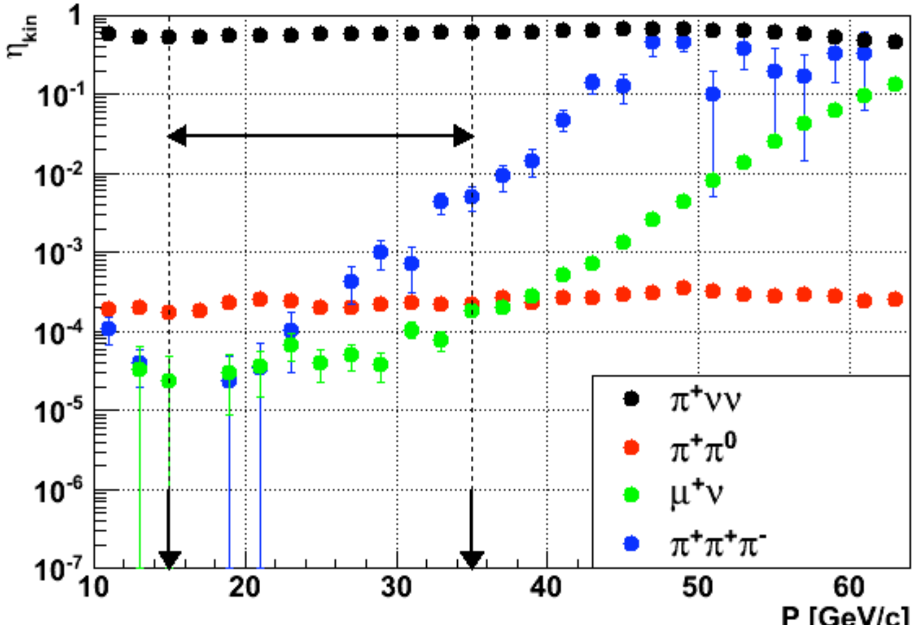
Acceptances after kinematic selection

Analysis:

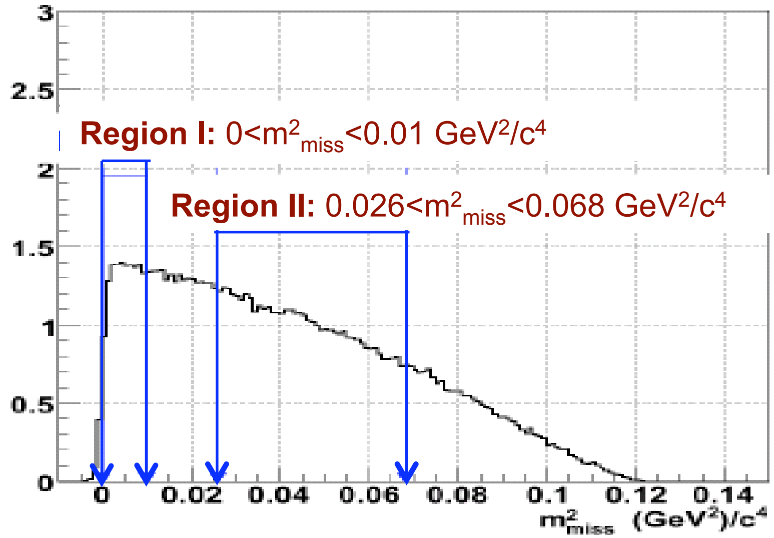
- Simulation based on G3, G4, Fluka
- **Main cut: $15 < P_{\pi+} < 35$ GeV/c**
  - for RICH operational reasons
  - better photon and muon rejection

Acceptance:

- 3.5 % in region I
- 10.9% in region II
- 50% signal loss due to $P_{\pi+}$ cut
- expected detector inefficiencies taken under consideration



Channel	M^2_{miss} cut	Overall acceptance
$\pi^+\nu\nu$	~ 0.57	~ 0.147
$\pi^+\pi^0$	$(2.2 \pm 0.5) \times 10^{-4}$	$(4.4 \pm 1.0) \times 10^{-5}$
$\mu^+\nu_\mu$	$(0.7 \pm 0.1) \times 10^{-4}$	$(1.0 \pm 0.1) \times 10^{-5}$
$\pi^+\pi^+\pi^-$	$(1.4 \pm 0.2) \times 10^{-4}$	$(6.9 \pm 2.0) \times 10^{-7}$



➔Acceptance: ~ 14.7 % (NA62 goal: 10%)

(to be taken into account: additional losses due to dead time, further inefficiencies, …)

NA62 Sensitivity

Decay mode	Events / year
Signal: $K^+ \rightarrow \pi^+ \nu\nu$ ***(Flux = 4.8 ×10¹² decays/year)***	**55 events/year**
$K^+ \rightarrow \pi^+ \pi^0$	4.3% (2.3 evts)
$K^+ \rightarrow \mu^+ \nu$	2.2% (1.2 evts)
$K^+ \rightarrow \pi^+ \pi^- e \nu$	<3% (1.7 evts)
Other 3-track decays	<1.5% (0.8 evts)
$K^+ \rightarrow \pi^+ \pi^0 \gamma$	~ 2% (1.1 evts)
$K^+ \rightarrow \mu^+ \nu \gamma$	~ 0.7% (0.4 evts)
others	negligible
Expected background	**<13.5% (7.4 evts)**

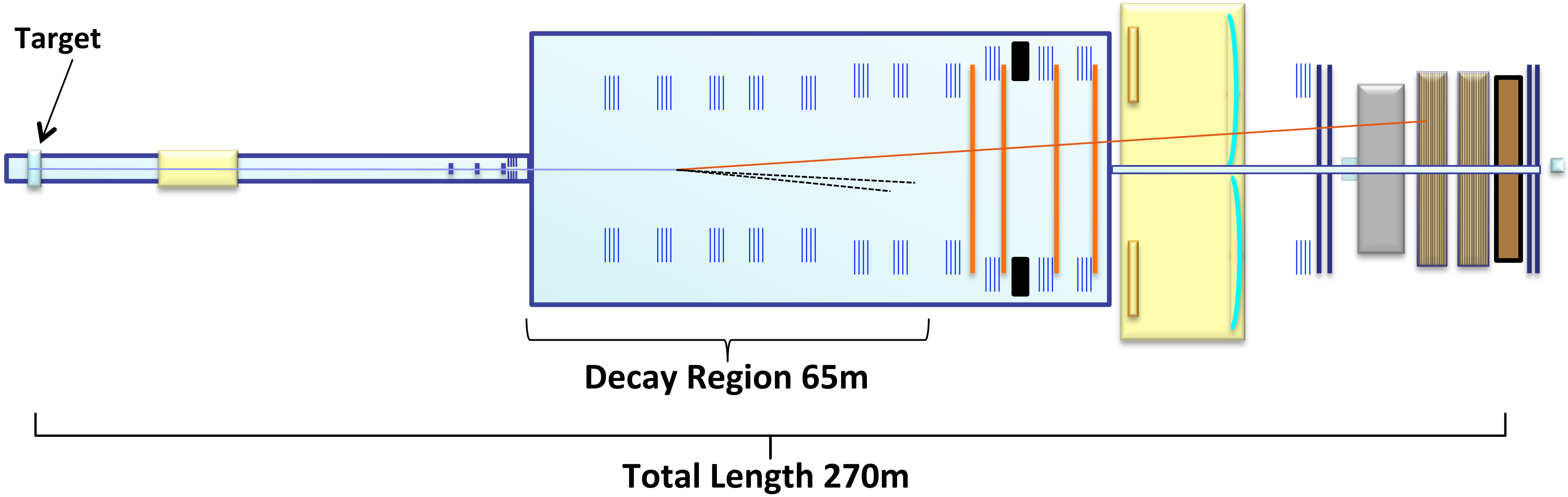
NA62: Beam & Detectors

Primary SPS beam: p = 400 GeV/c
- proton/pulse 3×10^{12} (×3 NA48/2)
- duty cycle 4.8/16.8 s

Secondary unseparated positive beam:
- p_K = 75 GeV/c ($\Delta p/p \sim 1.1\%$)
- π/K/p ($K^+ \sim 6\%$, positron free)
- K^+ decays / year = 4.5×10^{12} (×45 NA48/2)

Beam acceptance = 12 mstr (×25 NA48/2)
Area @ beam tracker = 16 cm^2
Integrated average rate = 750 MHz
Average rate @ detectors ≈ 10 MHz

Vacuum at 10^{-6} mbar to reduce beam-gas interaction
(use existing NA48 decay tank)



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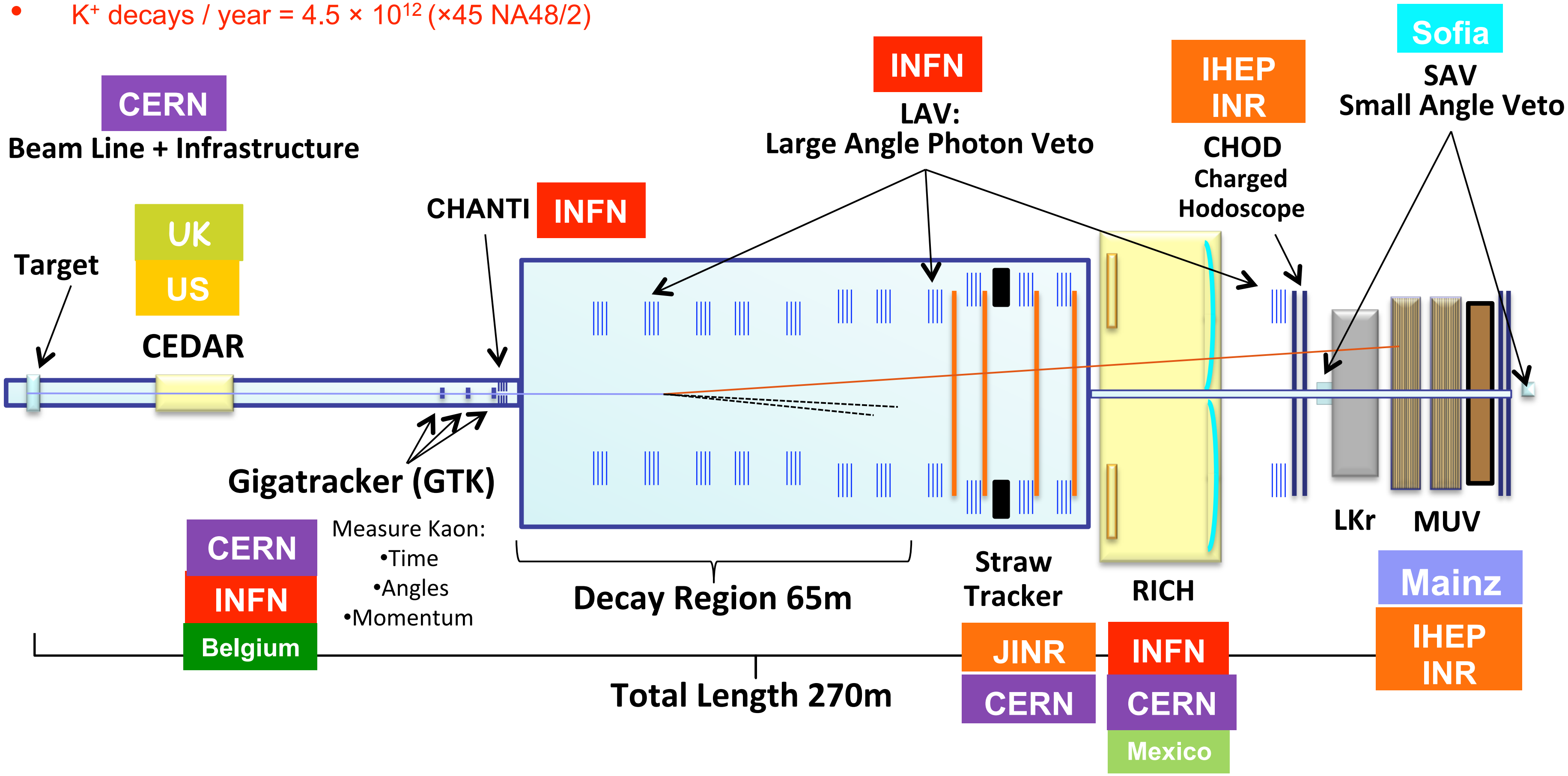

Status of the installation

- The completion of the new beam dump is a very significant achievement
- The beam line is being installed
- In progress tendering process for the vacuum system
- The surface building is being refurbished
- The detector is being installed in ECN3

ECN3 hall (same as NA48)

NA62: the main detectors

CEDAR: the Kaon Tagger (KTAG) ➔ PID: kaons

- It positively identifies the kaons before they enter the decay region.
- It must tag **~50 MHz of Kaons** and be as thin as possible.
- It must time-stamp the K^+ with an RMS of better than 100 ps in order to improve the association of the parent K^+ with the daughter π^+

Gigatracker (GTK) ➔ the beam Tracker

- Silicon Pixel tracker to measure direction and momentum on event-by-event basis.
- The beam rate is almost **1 GHz** (hence the detector name…).
- It must be very thin to avoid too many inelastic interactions…
- Excellent time resolution is required to time stamp each track **(< 200 ps / hit)**

Straw Tracker ➔ the decay charged particles Tracker

- A large acceptance spectrometer to reconstructs the decay charged particles.
- To reduce the multiple scattering, it is housed in the vacuum tank.
- The overall thickness of the 16 tracking views amounts to **less than 1% X_0**

Photon Vetoes + LKr Calorimeter ➔ the photon veto system

- A large system of detectors surrounding the decay tank to suppress the π^0 background by about **8 orders of magnitude** in a wide acceptance range.

RICH ➔ PID: pions, muons, positrons, …

- π/μ identification up to 35 GeV/c is achieved by means of a Ring Imaging Cherenkov Counter.
- It provides the time reference to correlate the pion to the correct incoming kaon track **(≤100 ps)**

Muon Vetoes ➔ PID: muons

- To suppress the muons at the trigger and analysis level.
- They consist of hadron calorimeters made of iron and plastic scintillator and a fast veto plane

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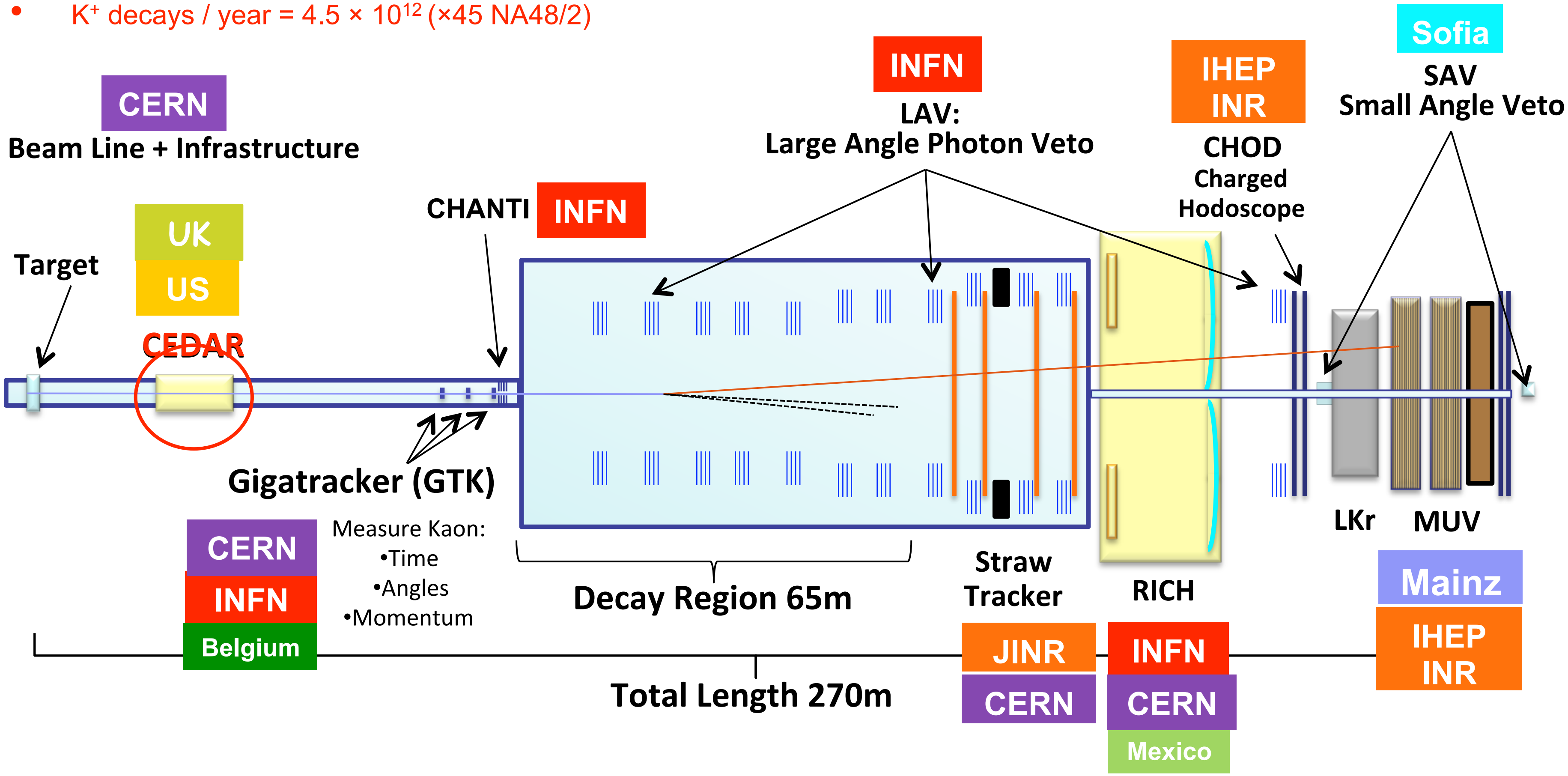
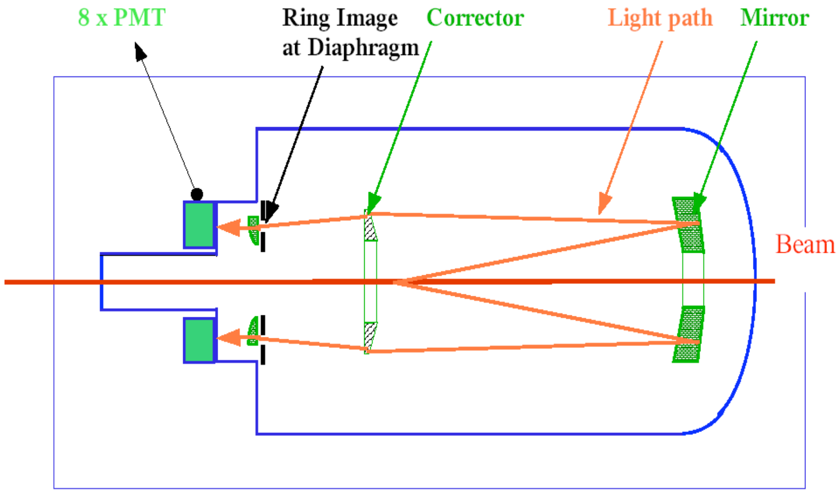


CEDAR

CEDAR: Cherenkov Differential Counter with Achromatic Ring Focus

CEDAR detectors have been used at CERN in early 80's for particle identification in the SPS secondary hadron beams.

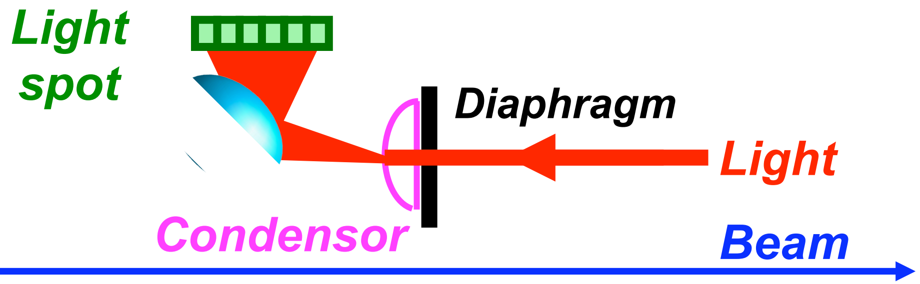
Gas pressure and diaphragm aperture are varied to select K (or other beam particles)

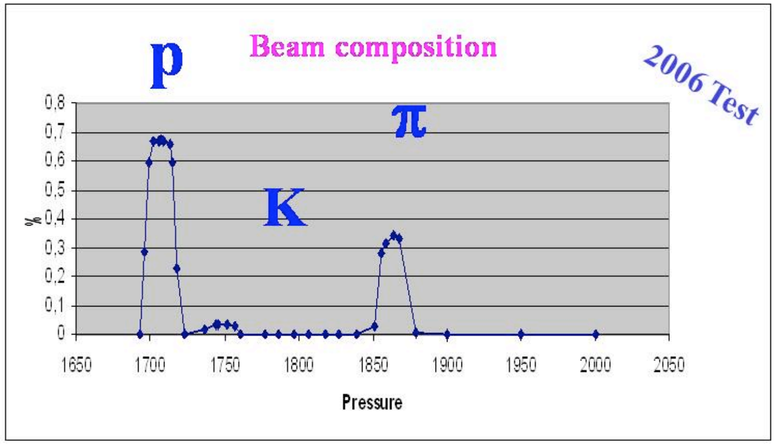


Original CEDAR (CERN 82-13)

Requirement for a CEDAR in NA62:

- positive K identification in a 800 MHz hadron beam, insensitive to π and p
- ~50 MHz K^+ rate (6% of total)
- photon rate = ~2 MHz/mm^2:
  - ➜ ~100 photons per Kaon on 8 spots
  - ➜ light to be diluted on many PMs (condensor)



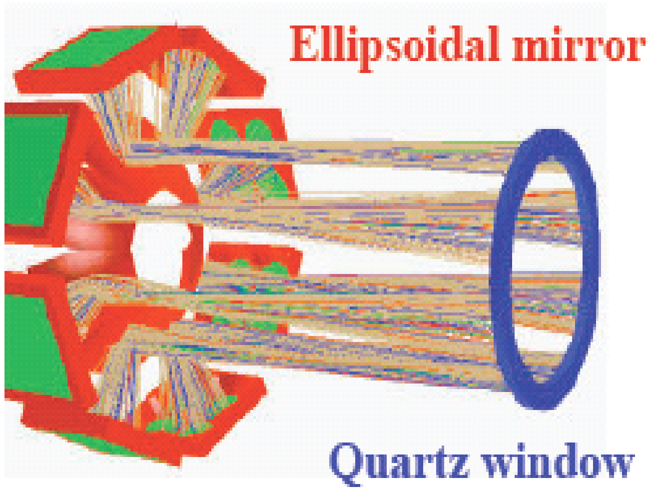


CEDAR: the Kaon Tagger (KTAG)

CEDAR counter filled with H_2 gas: with 50 MHz kaon rate one must spread the photon rate on many photo-detectors (PMs)

KTAG: CEDAR adapted to the NA62 need

- ➔ H_2 instead of N_2 gas to minimize multiple scattering
- ➔ nominal pressure for kaons: 3.85 bar
- ➔ 64 PMs (Hamamatsu R7400U-03) per light spot
- ➔ new deflecting mirrors system to decrease the rate per single channel on the readout
- ➔ modified mechanics/optics
- ➔ new front-end and readout electronics

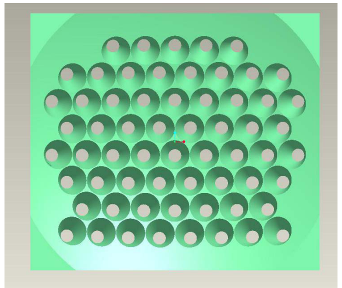


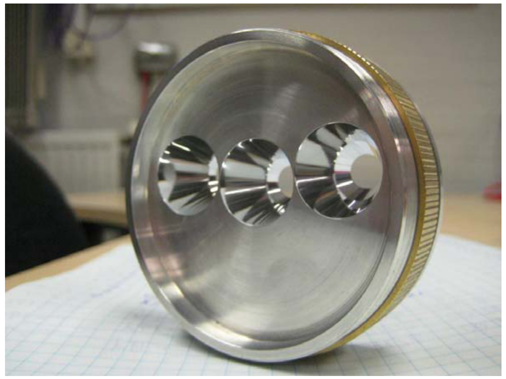
PMT plane

CEDAR detector commissioning for NA62 successfully completed (2011 CERN test beam)

- ➔ new PMs and light guide prototype show adequate efficiency and timing performance
- ➔ different options of new frontend and read-out electronics were tested to validate the final choice

Light spot (64 PMs)

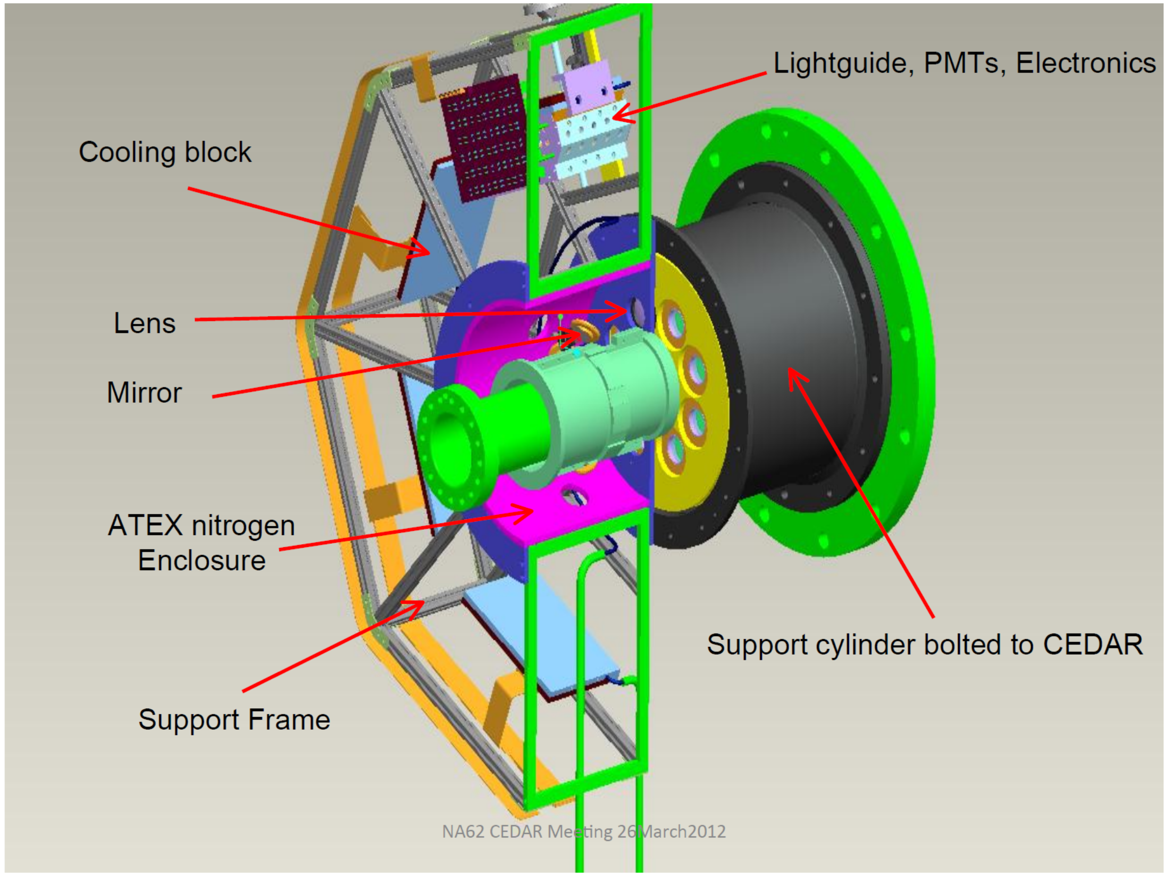




Aluminum light-guide (prototype)

CEDAR: the Kaon Tagger (KTAG)

- In the 2012 Technical Run the full KTAG enclosure will be available.
- The light guides, electronics and cooling plates will be installed for 4 out of 8 light spots.
- Each light spot will be read out by 32 instead of 64 photomultipliers (PMs).



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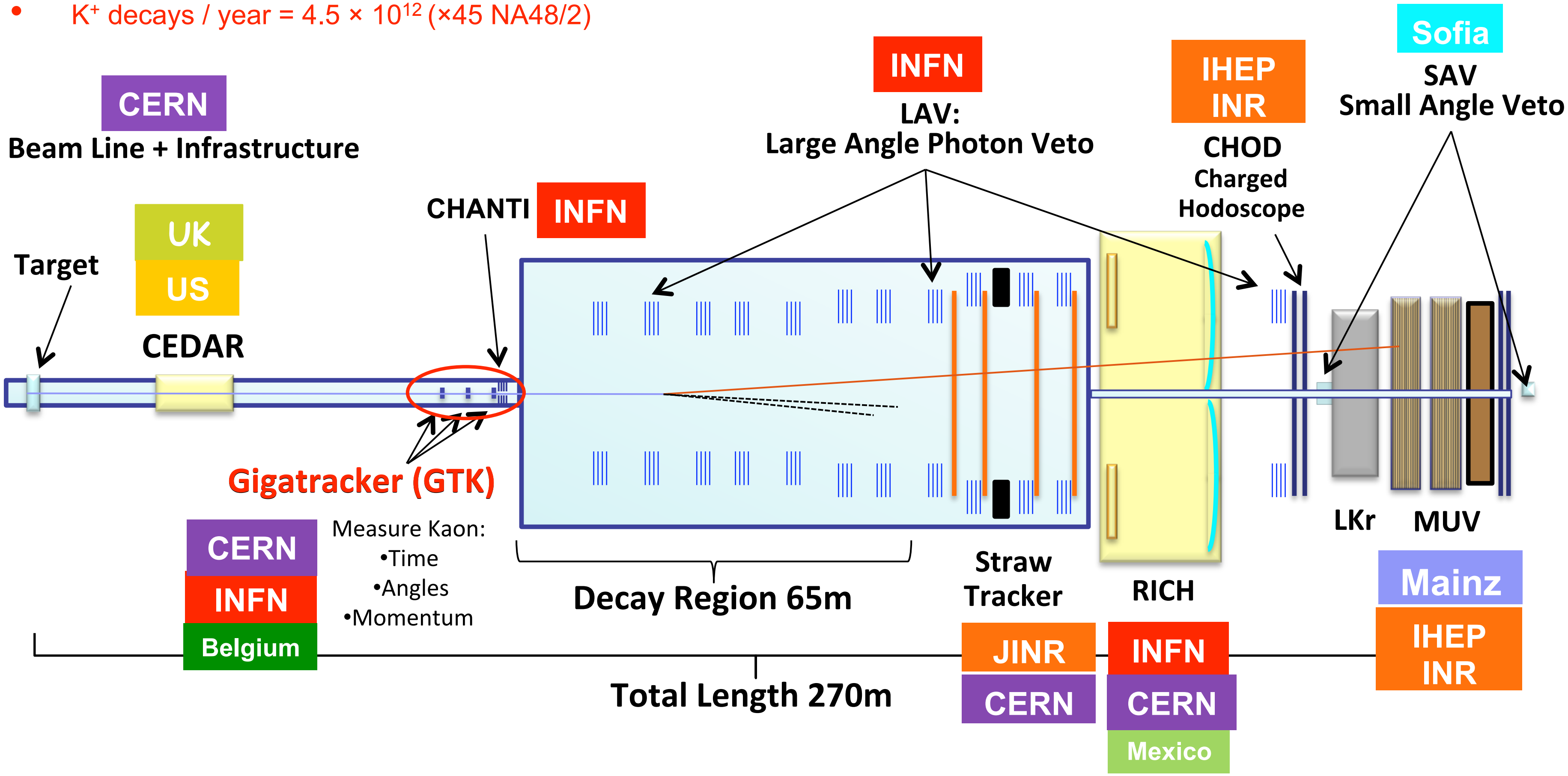
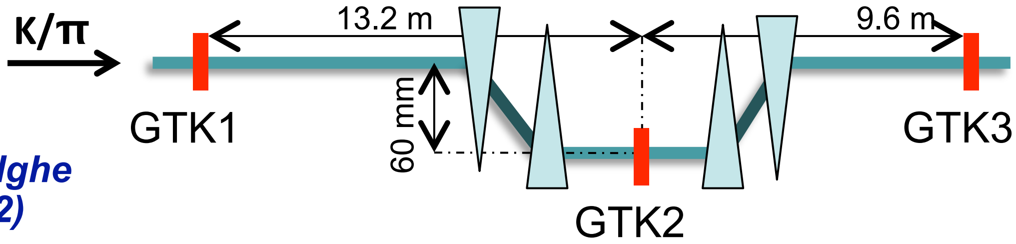
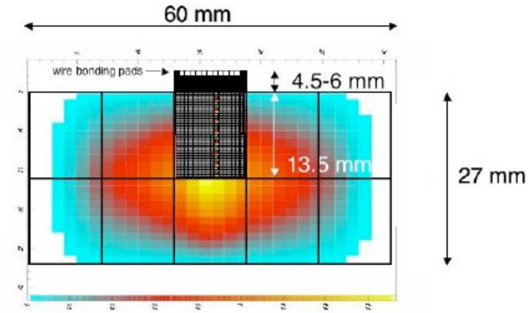


Gigatracker (GTK)

GTK: beam spectrometer to measure time, direction and momentum of all the particle tracks in a **800 MHz** beam

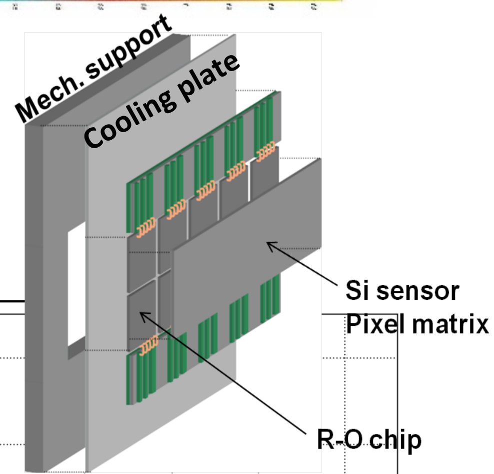


(see Bob Velghe at PSPX12)



Three hydrid Si-pixel stations before the decay volume

- 200 μm thick Si sensor (60 x 27mm^2)
- 18000 pixel/station, 300 x 300 μm^2 pixel size
- thin detector: 200 μm sensor + ~100 μm readout chip (<0.5%X/X_0 per station)
- 10 readout chips thinned down to 50-100 μm, bump-bonded to the sensor (0.13 μm technology)
- dimensions matching the beam shape

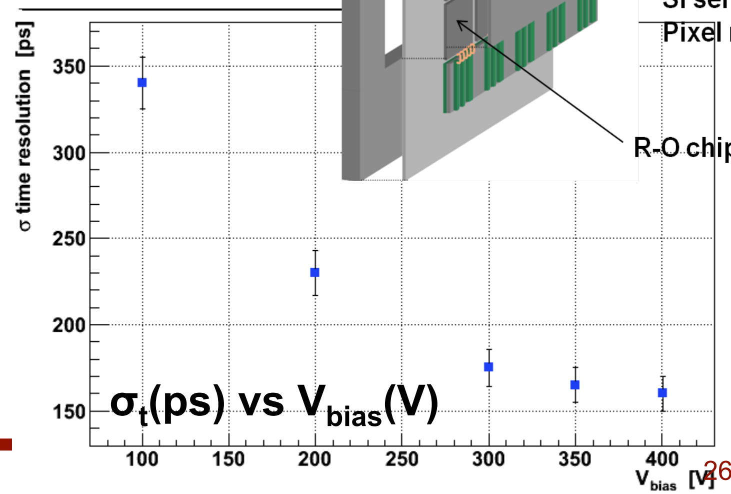


Performances:

→ **direction: $\sigma_{RMS}(\theta_K)$ ~16 μrad**

→ **momentum: $\sigma_{RMS}(p_K)$ /p ~0.2%**

→ **track time: $\sigma_{RMS}(t)$ ~150 ps** on single tracks



GTK: Micro-Channel Cooling

Expected fluence (100 running days/year) ~ 2 x 10^{14} (1 MeV n_{eq}/cm^2)

➔ **High radiation levels** (comparable to inner layers of LHC trackers in 10 years)

➔ **require an efficient cooling system to control the leakage current**

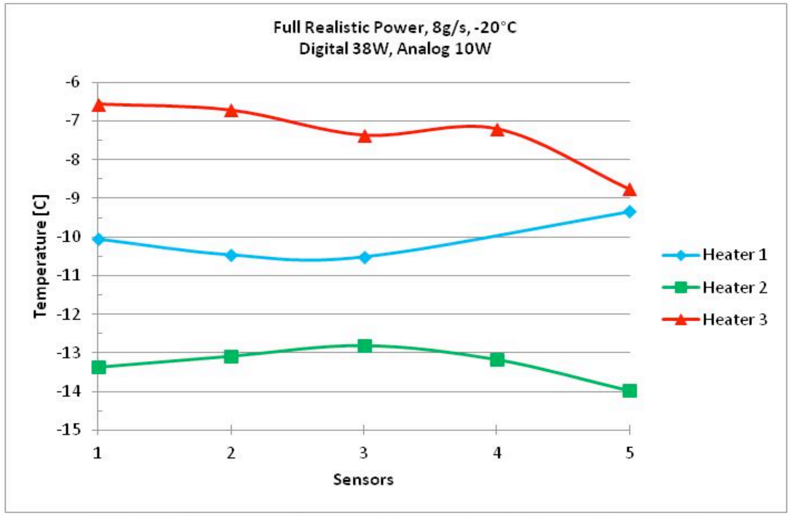
Micro-channel technology recently chosen as baseline solution:

- 150 mm thickness, two-inlet and two-outlet pipe and appropriate geometry

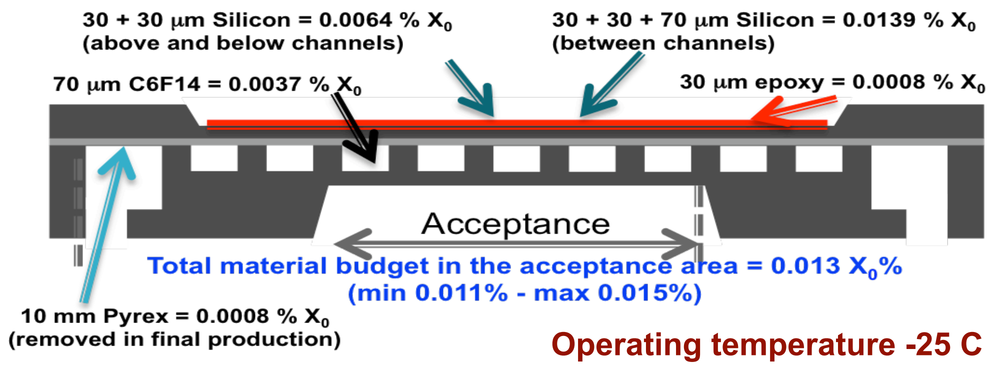
Performances established with a ceramic mock-up:

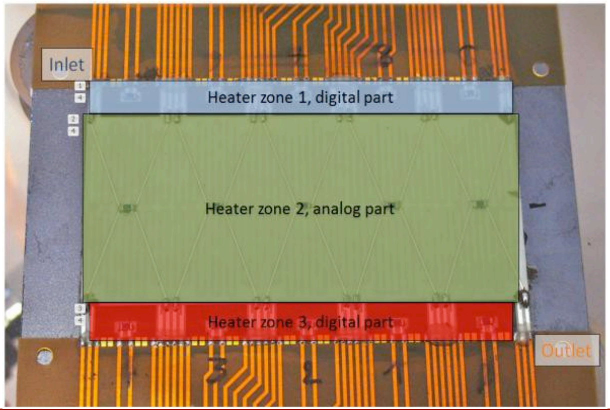
- temperature uniformity over the detector is about 7 ^{0}C

Prototype ready soon for further testing



Cross section of the cooling plate





Operating temperature -25 C

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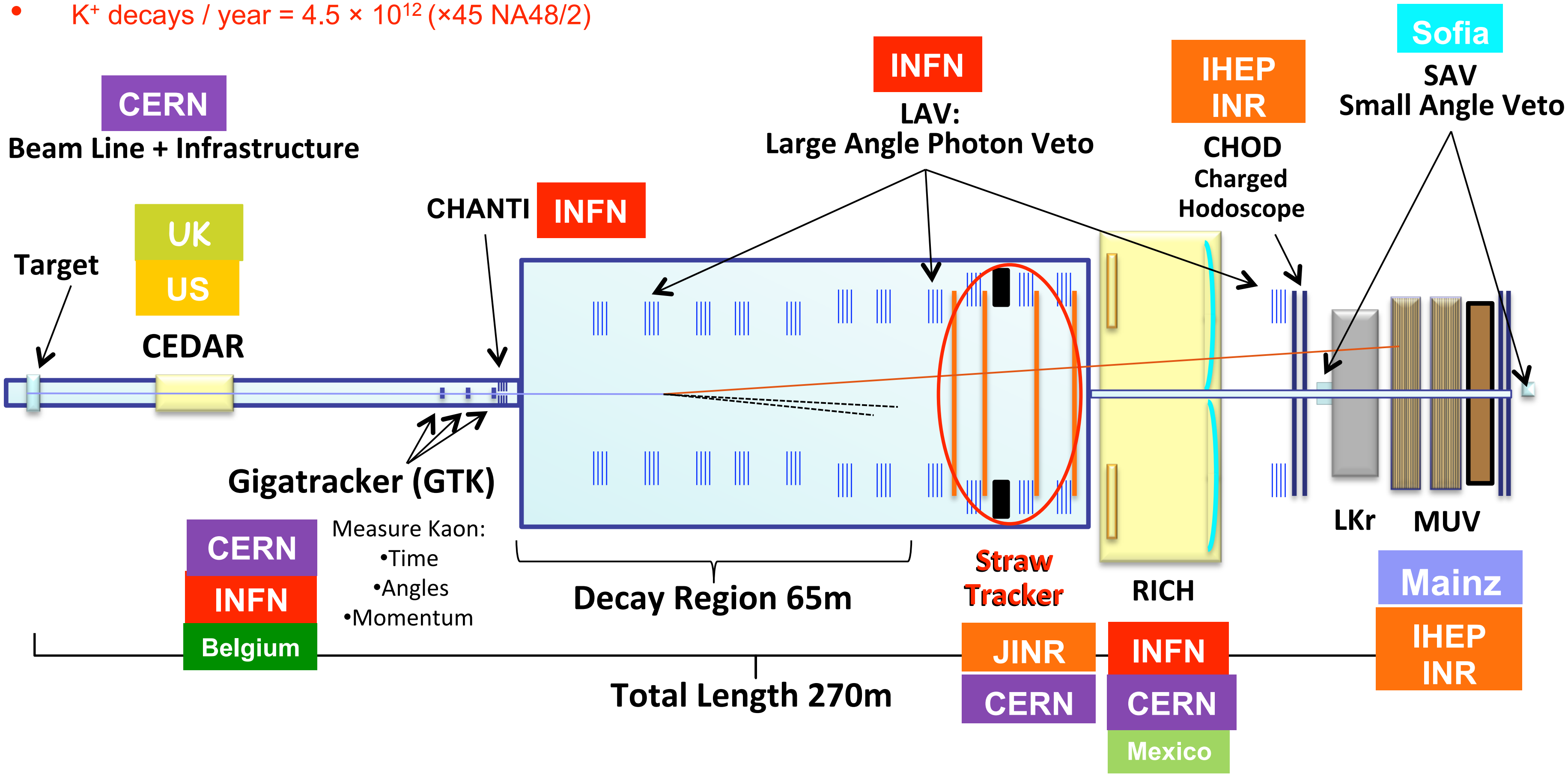
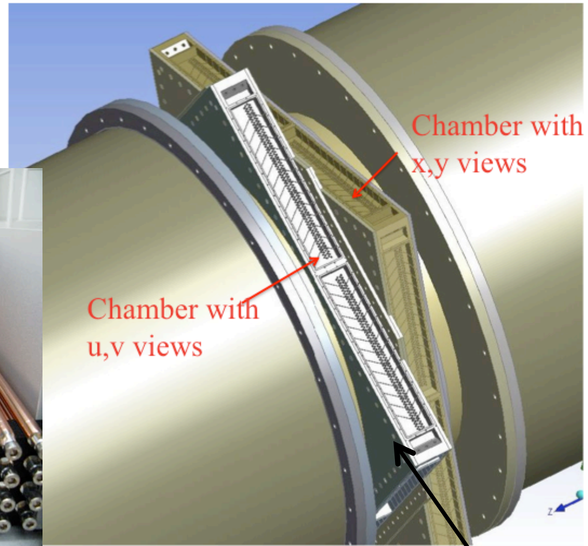
(use existing NA48 decay tank)



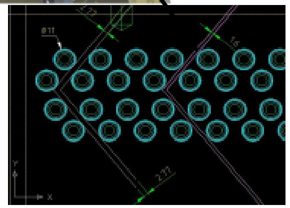
Straw Spectrometer

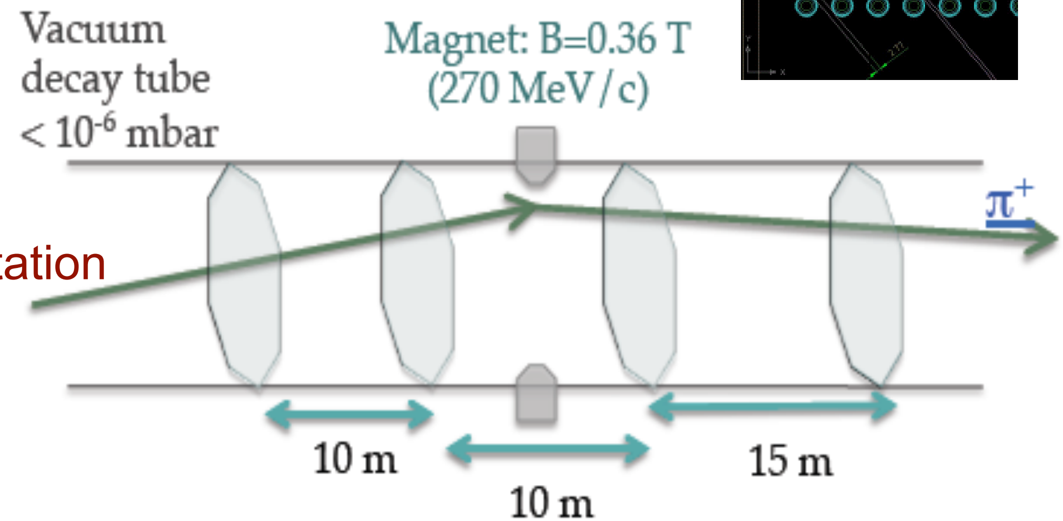
The Straw Tracker: large acceptance spectrometer to reconstructs coordinates and momentum of charged particles originating from the decay region with $\Delta p/p<0.5\%$ and $\sigma_{xy}<120\mu m$

- 4 stations of straw tubes:
  - → 36 μm Cu/Au-plated mylar foils
  - → lenght 2.1 m, diameter 9.6 mm
  - → ~1800 tubes per station
- 4 views (XYUV) per station
- 4 staggered layers per view
- mechanically independent straws
- central "hole" (6 cm radius)
- Minimum material: ~0.5% X_0 per station
  - → no window or He gas
  - → working in vacuum (10^{-6} mbar)
- gas mixture: Ar(70%) + CO_2 (30%)



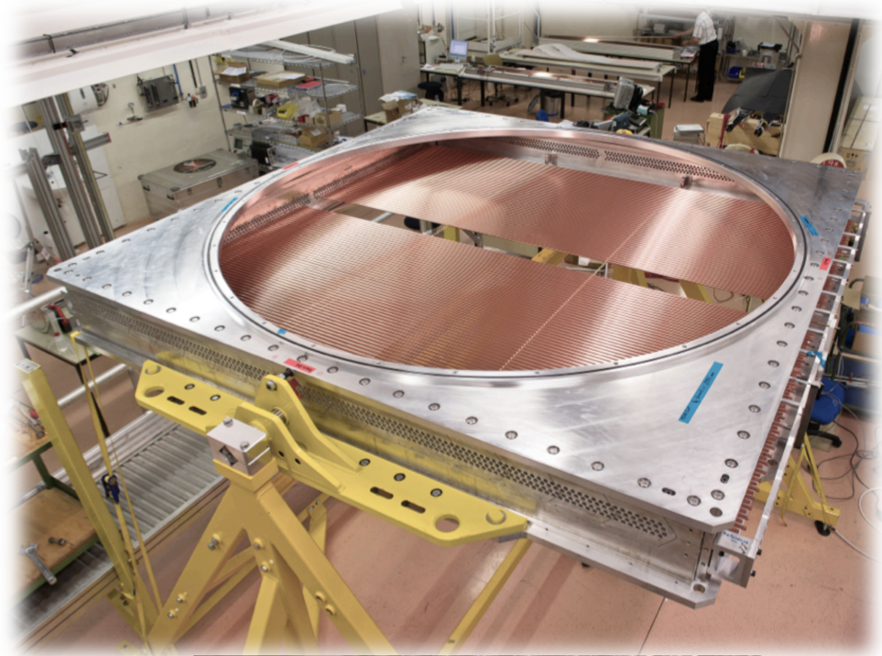
Straw layout in one view





Straw Spectrometer

Full length prototype built and tested in vacuum in 2007 and 2010 at SPS@CERN

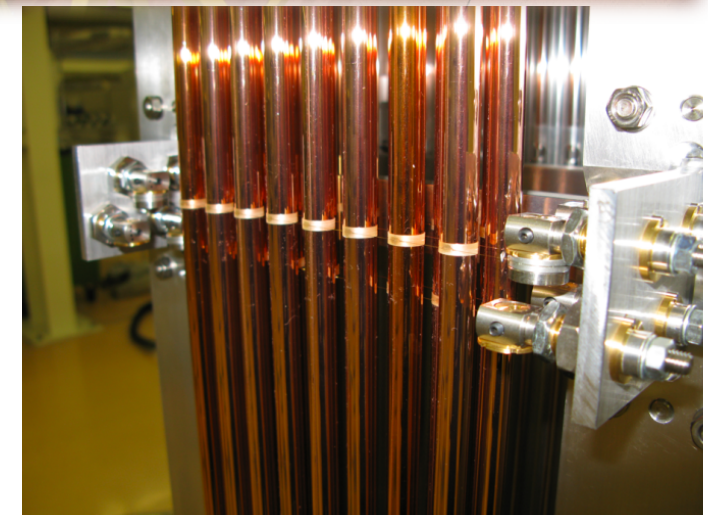


Momentum and angular resolutions

→ $\sigma(P_p)/P_p \sim 0.3\% \oplus 0.007\% * P_p$ (GeV/c)

→ $\sigma(dX/dZ)/(dX/dZ) \sim$ 45-15 μrad

→ $\sigma <$ 130 μm per view



Efficiency > 99% on single hit for the straw center at low rate

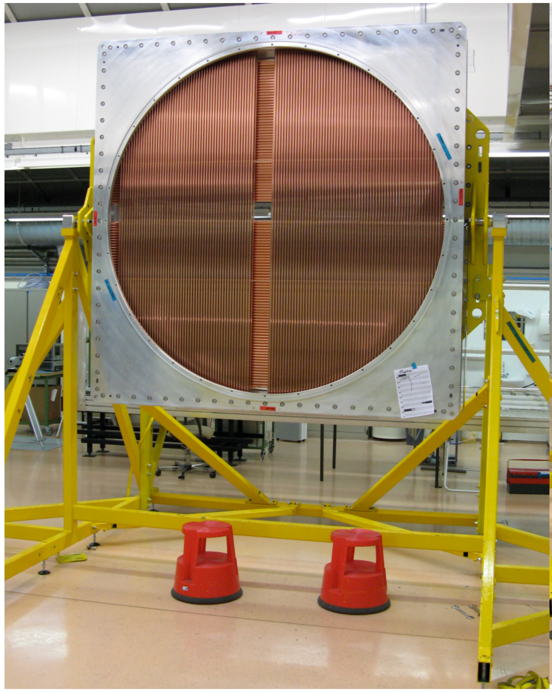
High rate: 0.5 MHz maximum with < 3% lost efficiency

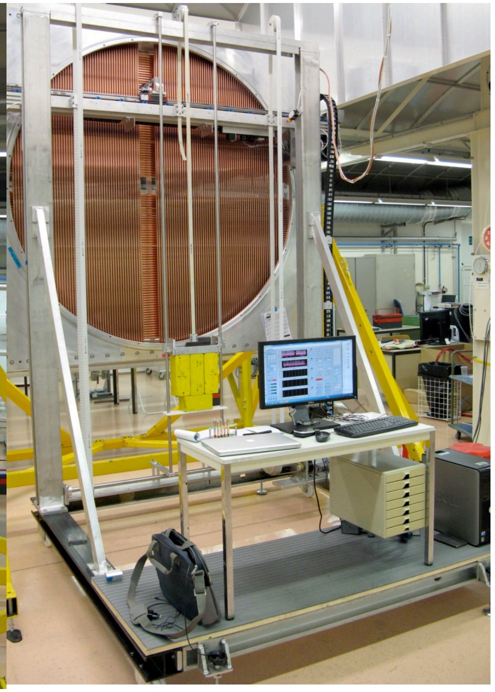
Vertex extrapolation: $\sigma_{CDA} \sim 1$ mm

Kinematic rejection power expectation (MC):
$\sim 10^4$ ($K^{\pm}_{2\pi}$), $\sim 10^5$ ($K^{\pm}_{2\mu}$)

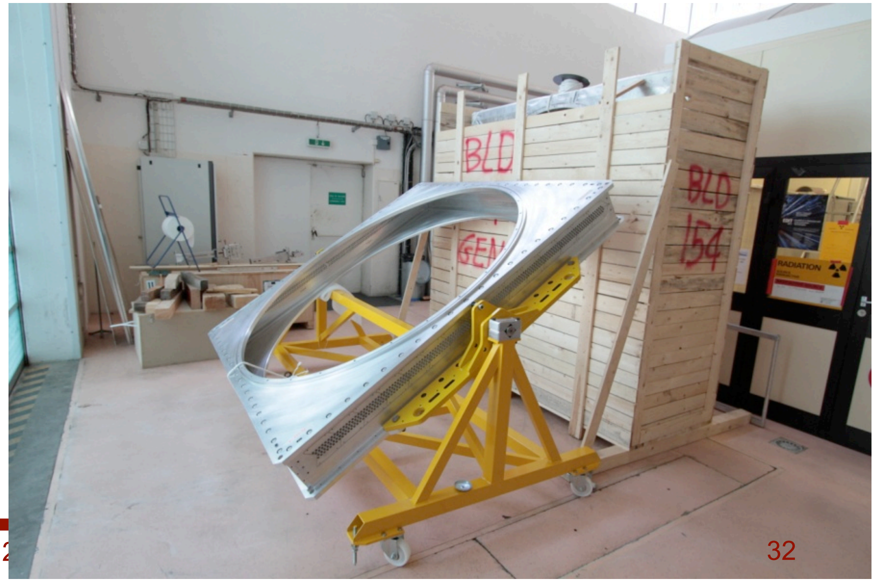
Straw modules

Module 1, 896 straw tubes



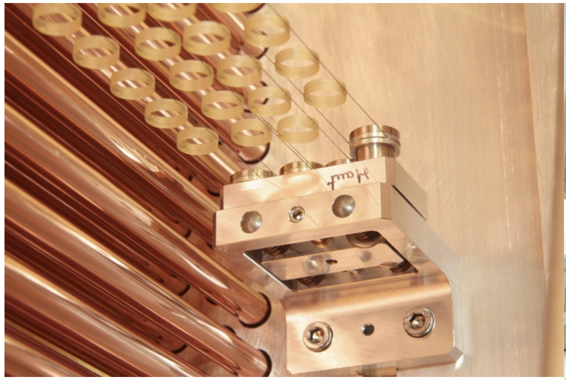


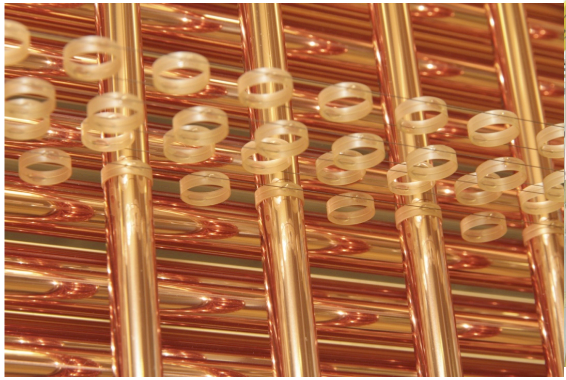
Module 2: leak testing started

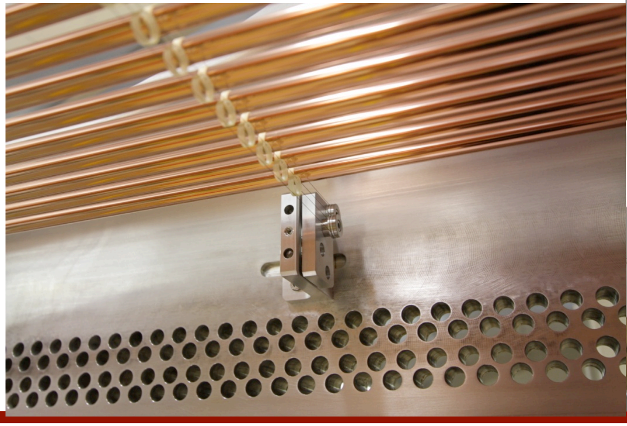


Module 3 (Dubna): unpacking,
sealing , leak test

Straw: module assembly







Spacers

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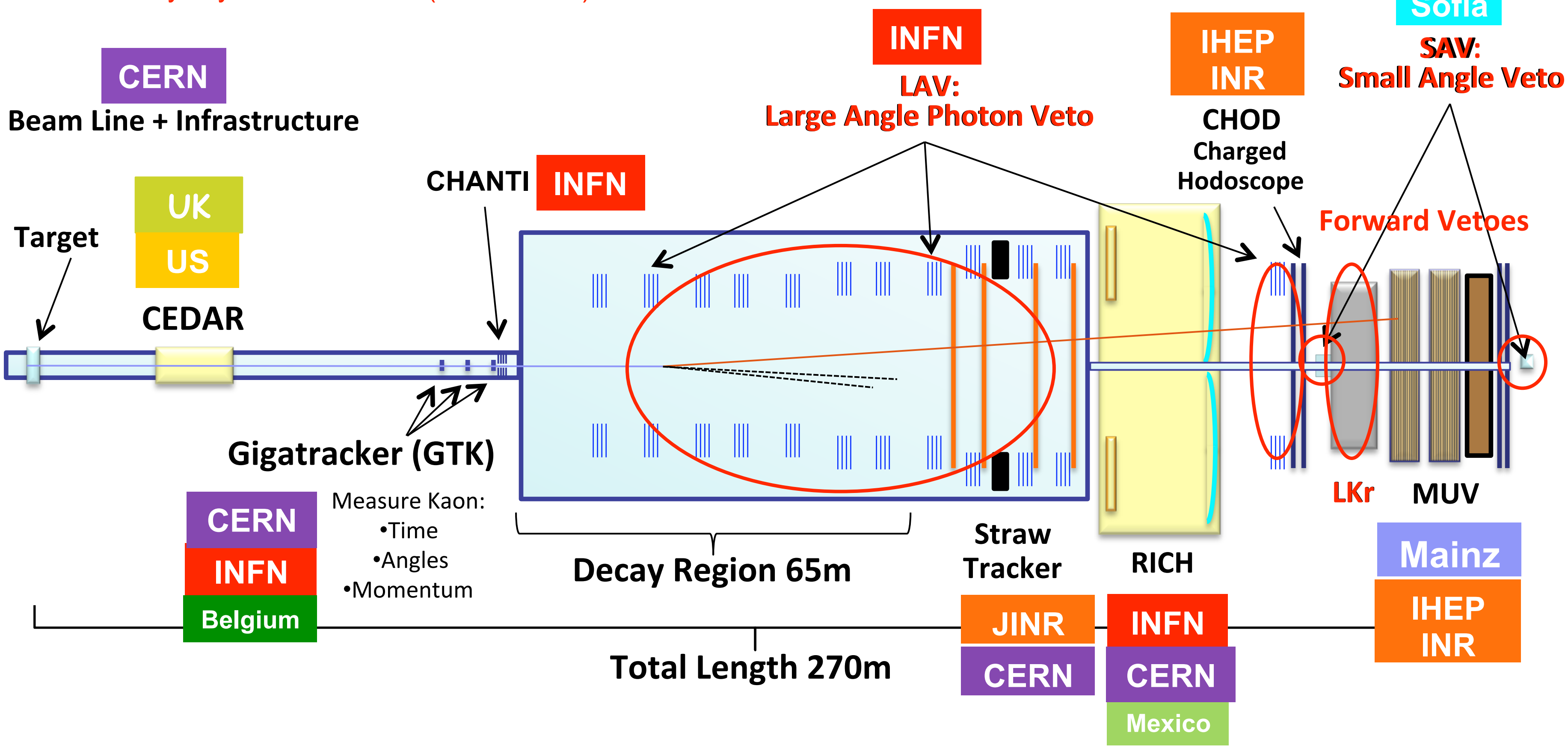
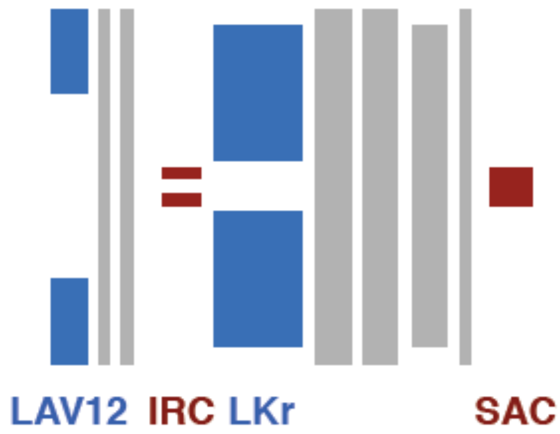


The NA62 Photon Veto

BR($K^+ \rightarrow \pi^+\pi^0$) = 21% ➔ Kinematic rejection: 10^{-4}

Photon Veto Detectors inefficiency:

Detector	θ(mrad)	Maximum 1-ε	
LAV	8.5 - 50	10^{-4} at 200 MeV	Large angle, new system
LKr	1 – 8.5	10^{-3} at 1 GeV 10^{-5} at 10 GeV	Medium angle, re-use NA48 LKr calorimeter
SAV (SAC+IRC)	< 1	10^{-5}	Small angle, new system of compact calorimeters



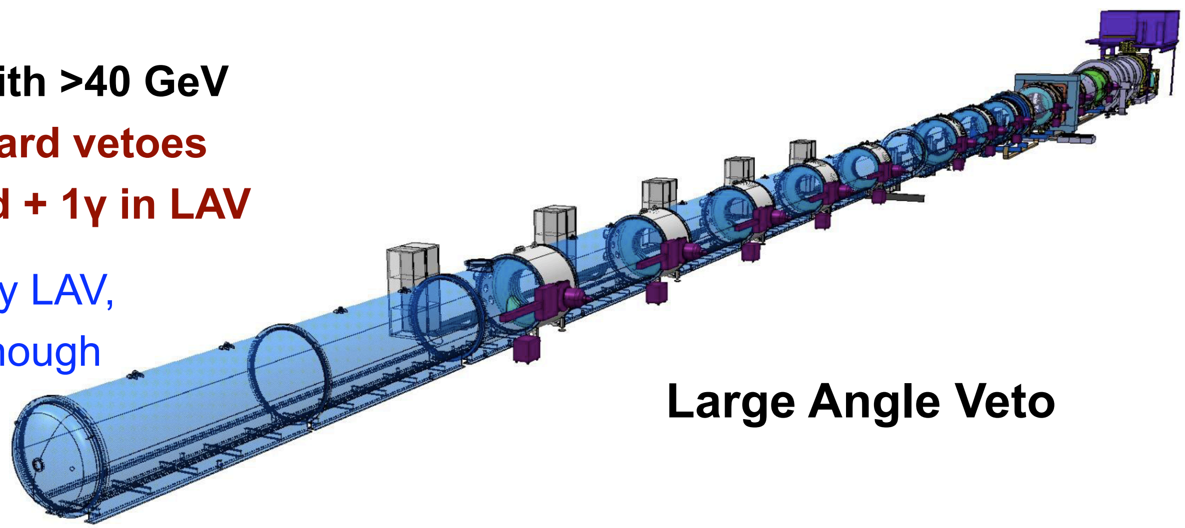
Forward Vetoes

Cut $p_{\pi+}$< 35 GeV gives $\pi^0 \rightarrow \gamma\gamma$ with >40 GeV

→ 85% of events have 2γ in forward vetoes

→ 15% of events have 1γ forward + 1γ in LAV

→ In case of undetected photons by LAV, the other γ from π^0 decay has enough energy to be detected efficiently by LKr & SAC (**LAV simulation**)

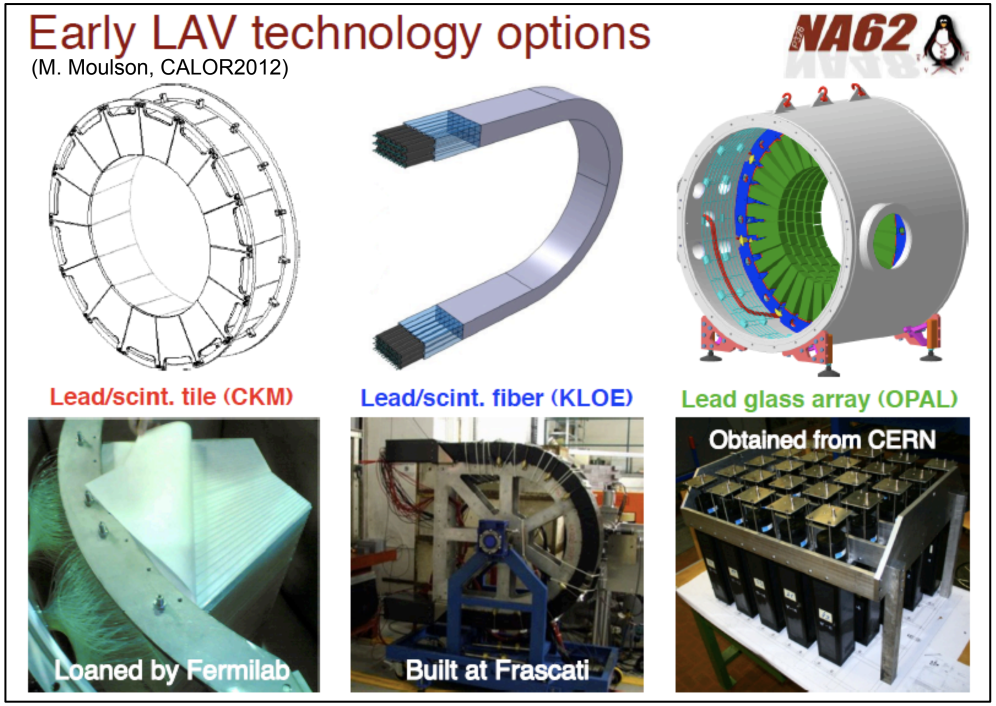


Large Angle Veto

The Large Angle Veto (LAV)

LAV system requirements:

- Efficiency 10^{-4} for E_γ>200 MeV
- Operation in vacuum (10^{-6} mbar)
- Dynamic range 10 MeV – 10 GeV
- Energy resolution ~ 10% at 1 GeV
- Time resolution ~ 1 ns



Protoypes tested with e± in 2007-08 at the LFN BTF: all 3 technologies show satisfactory efficiency:

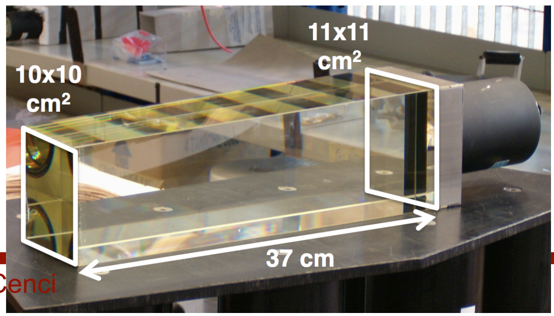
- Inefficiency $<10^{-4}$ for $E_{e\pm} \le 471$ MeV

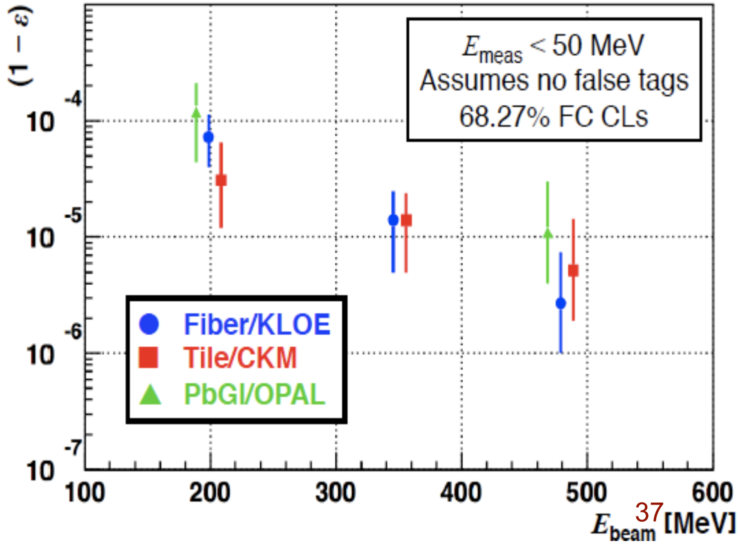
Lead-glass (Schott SF57) modules from OPAL selected

→ free for use in NA62

→ 3600 total, different geometries, minor differences

→ R2238 76-mm PMT (12 stages, gain: 5×10^5@1250V)

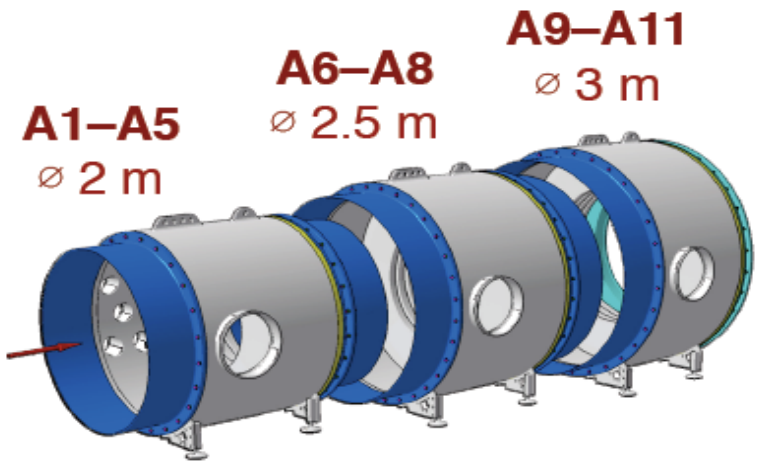


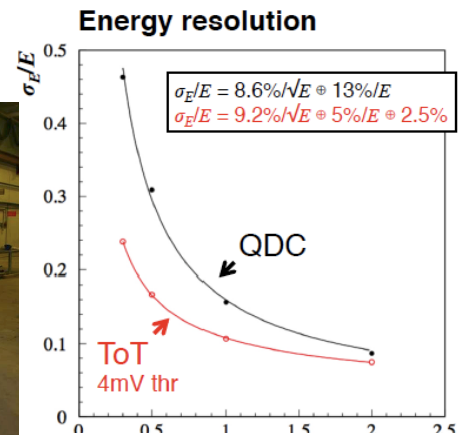


The Large Angle Veto (LAV)

LAV System Design

- Hermetic coverage in the 8.5-50 mrad range
- 12 ring stations of increasing diameter along the decay volume ➔ suppress γ from K decays between 105 m to 170 m after the target
- Spaced by 6 m in the upstream region and by 12 m downstream, different dimensions
- Stations A1-A11 operated in vacuum
- Station A12 operated in air (design not final yet)
- 4 or 5 staggered rings of lead-glass crystals per station
- 32 to 48 crystals/layer, >2500 crystals in total
- Incident particles hit blocks in at least 3 rings (21 X_0)
- Most particles traverse 4 rings (27 X_0)
- Total depth of 29 to 37 X_0





Test beam results (CERN 2010):

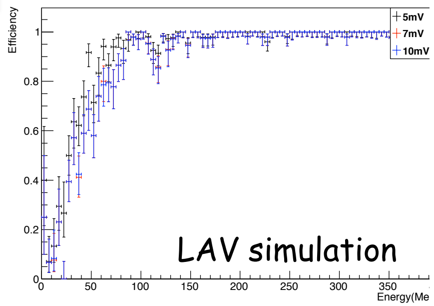
Energy resolution:

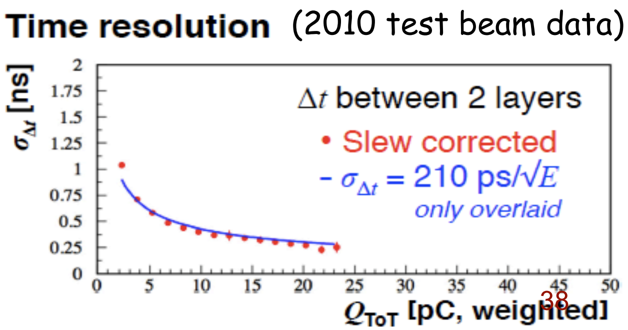
$\sigma_E/E = 0.092/\sqrt{E} \oplus 0.05/E \oplus 0.025$ [GeV]

Time resolution (slewing corrected):

$\sigma_t = 300$ ps$/\sqrt{E(\mathrm{GeV})}$

Inefficiency within expectation (LAV simulation)





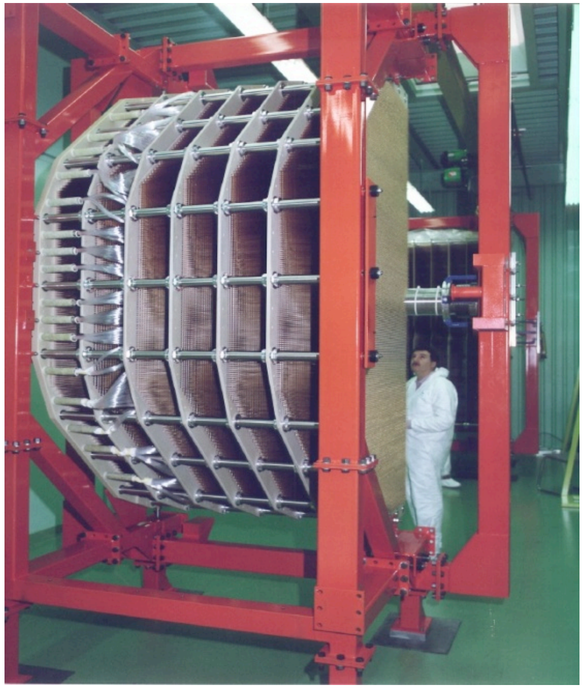
LAV: installation status

First 8 stations completed and installed in the beam line

LKr: medium angle veto

Medium angle veto (1-8 mrad) → inefficiency $<10^{-5}$ for E_γ > 10 GeV

- Liquid Krypton NA48 electromagnetic calorimeter
- Quasi homogeneous ionization chamber
- More than 13000 channels, 2x2 cm^2 granularity
- Depth 1.25 m, 27 X_0
- Excellent energy resolution:
  $\Delta E/E = 3.2\%/\sqrt{E} \oplus 9\%/E \oplus 0.42\%$ [GeV]
- Very good time resolution: 100 ps
- New readout electronics: 14 bits 40 MHz FADC with large data buffering, 14 bit resolution:
  - 5 prototypes (CAEN) available in 2012



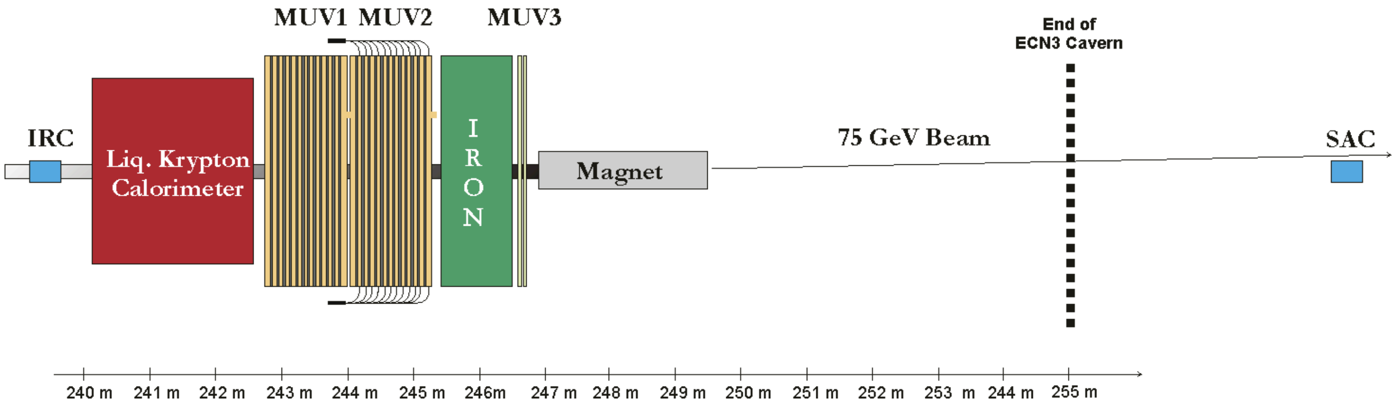
Performance of LKr as photon veto

→ measured using NA48 data @75 GeV
→ $K^+ \to \pi^+\pi^0$ selected using kinematics only
→ π^+ and lower energy γ are used to predict the position of the other γ

Energy(GeV)	Inefficiency
2.5-5.5	10^{-3}
5.5-7.5	10^{-4}
7.5-10	5×10^{-5}
>10	8×10^{-6}

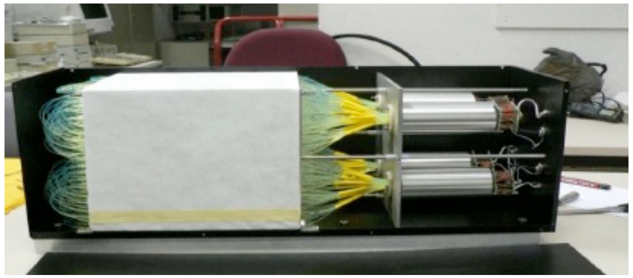
The Small Angle Veto

Small Angle Veto (<1 mrad): two small calorimeters made of layers of lead and scintillators with wavelength shifting fibers ("shashlyk")



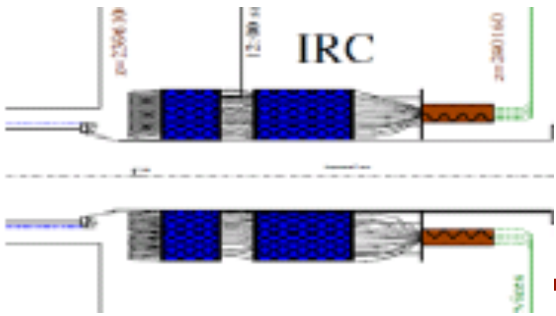
SAC: Small Angle Calorimeter

- close to the beam dump, at the very end of the experiment, in the prolongation of the beam pipe region, to detect γ down to 0 degrees.
- a magnet will deflect charged particles before it



IRC: Inner Ring Calorimeter

- located around the beam pipe, in front of LKr, cover the angular region close to the inner LKr radius (radial coverage: 7 cm < R < 14 cm)



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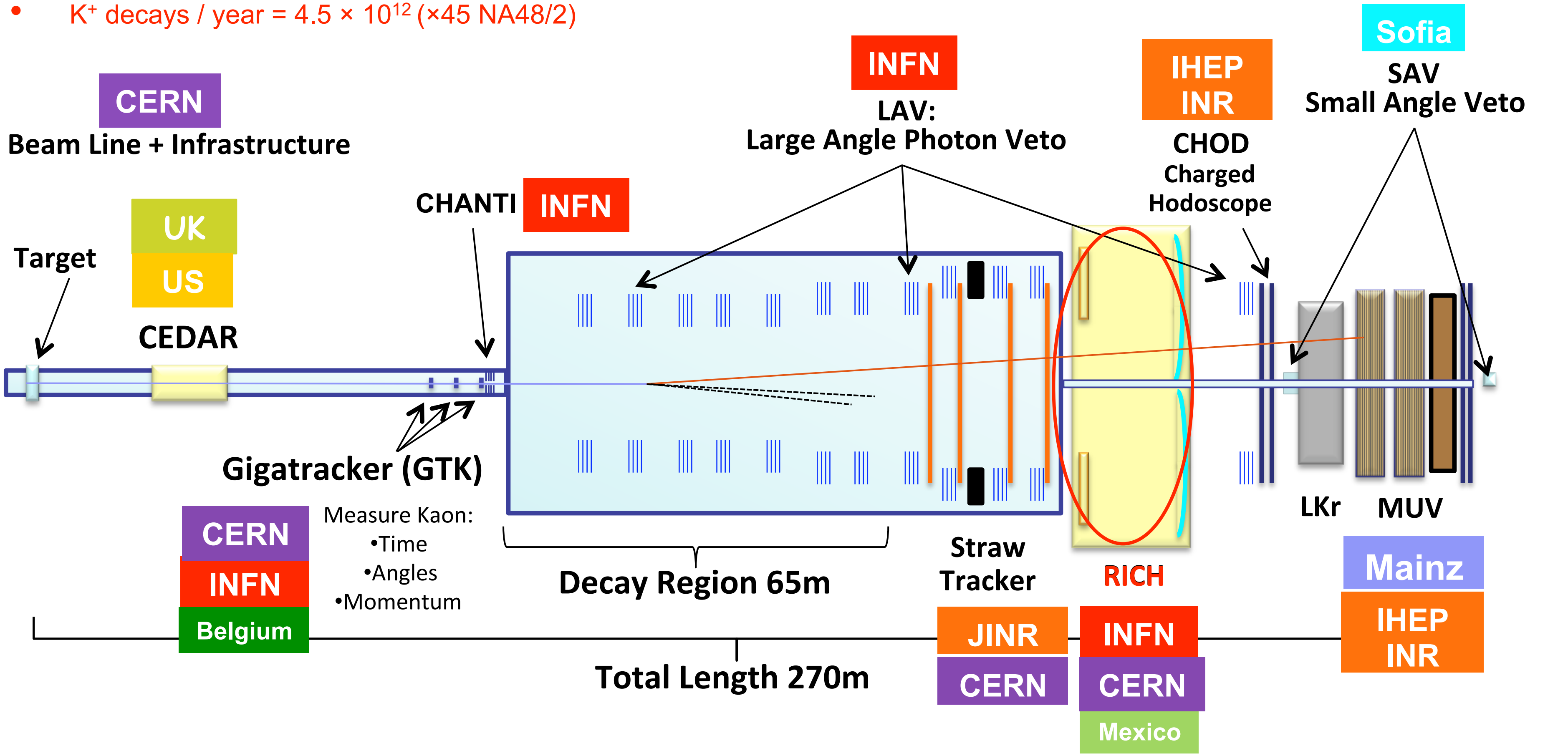
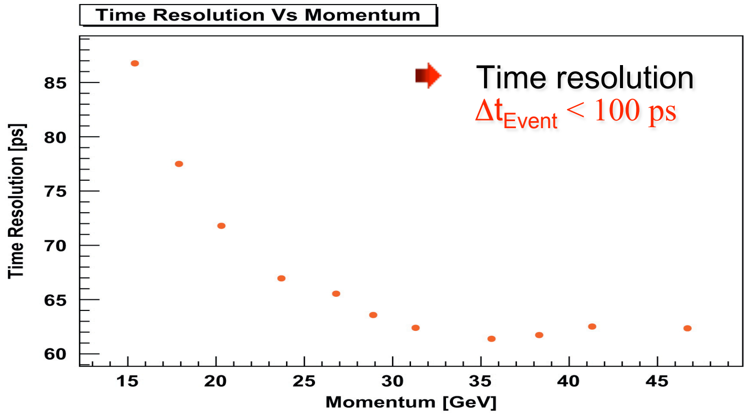


RICH

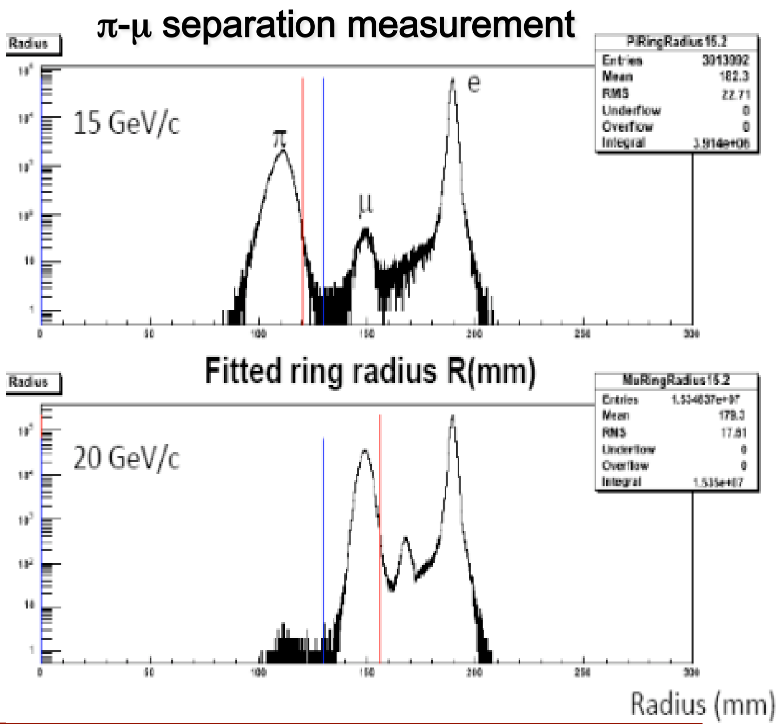
REQUIREMENTS:

- Separate π-μ in $15 < p < 35$ GeV/c with μ suppression factor $\leq 10^{-2}$
- Measure the π crossing time with a resolution < 100 ps
- Provide a L0 trigger for charged tracks



The NA62 RICH

- 17 m long, 3 m diameter vessel
- Neon gas radiator at atmosferic pressure
  - → *(n-1) = 62.8 10^{-6} at λ=300 nm (small dispersion)*
  - → *low atomic number: small X_0*
  - → *$(\theta_{Ch})max$ = 11.2 mrad*
  - → *$p_{threshold}$ = 12 GeV/c for π*
- Cherenkov light collected in 2 spots of ~1000 PM each
- Mosaic of mirrors with 17 m focal lenght
- Design validated in full length prototype tests at CERN

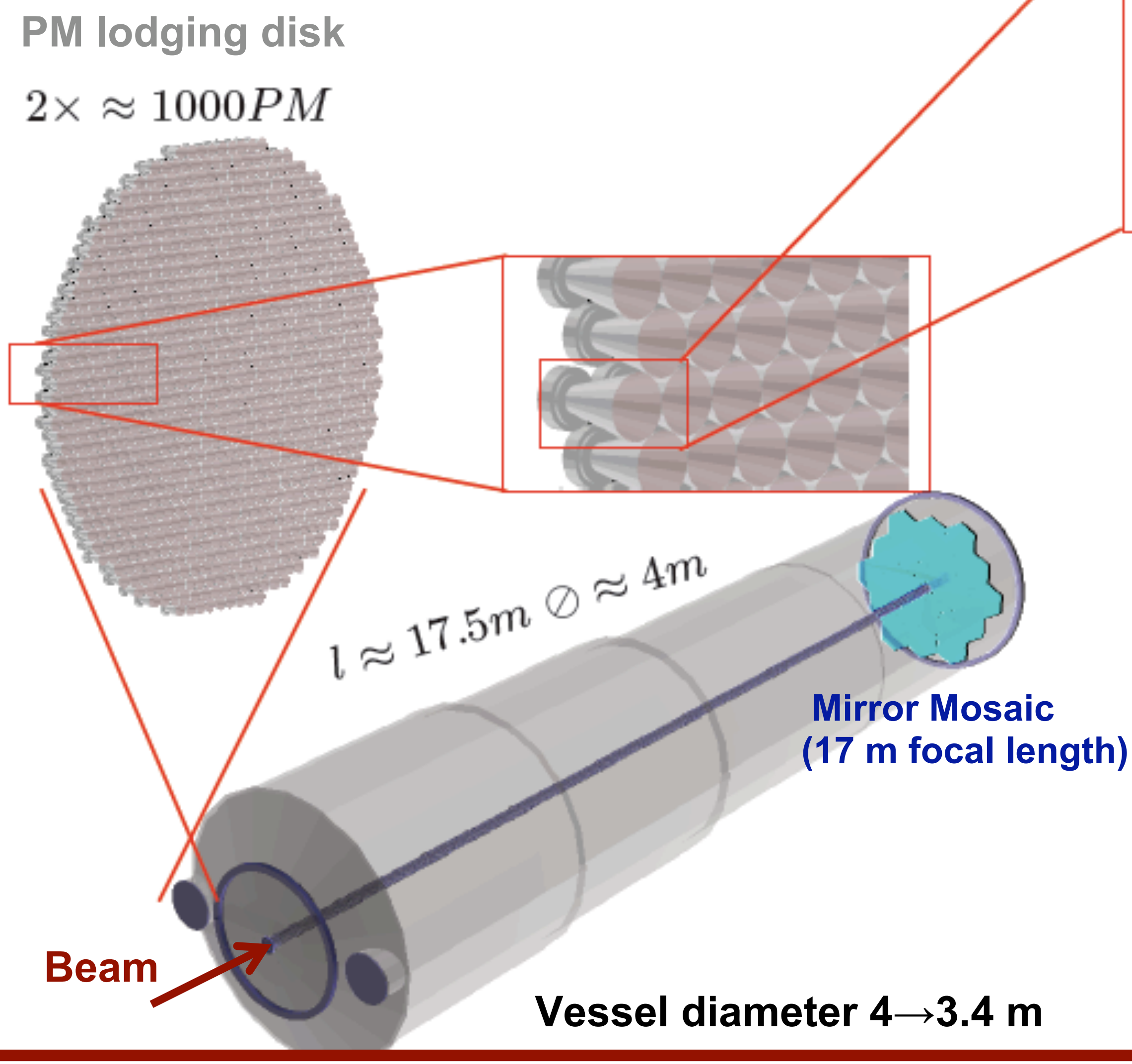


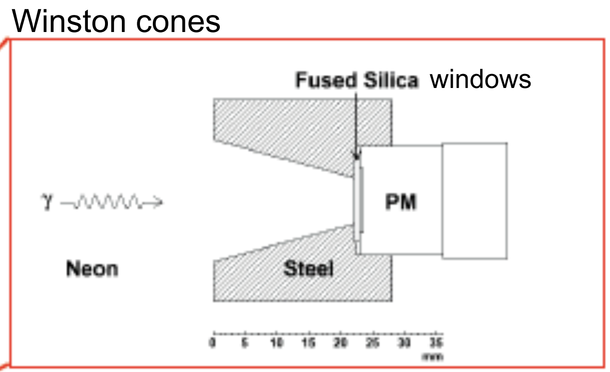
TEST BEAM RESULTS

[NIM A 593, 2008; NIM A621, 2010]

- Average time resolution: ~70 ps
- Integrated π-μ mis-identification probability: ~$5x10^{-3}$
- θ_{Ch} resolution ~60 mrad

RICH Final Design

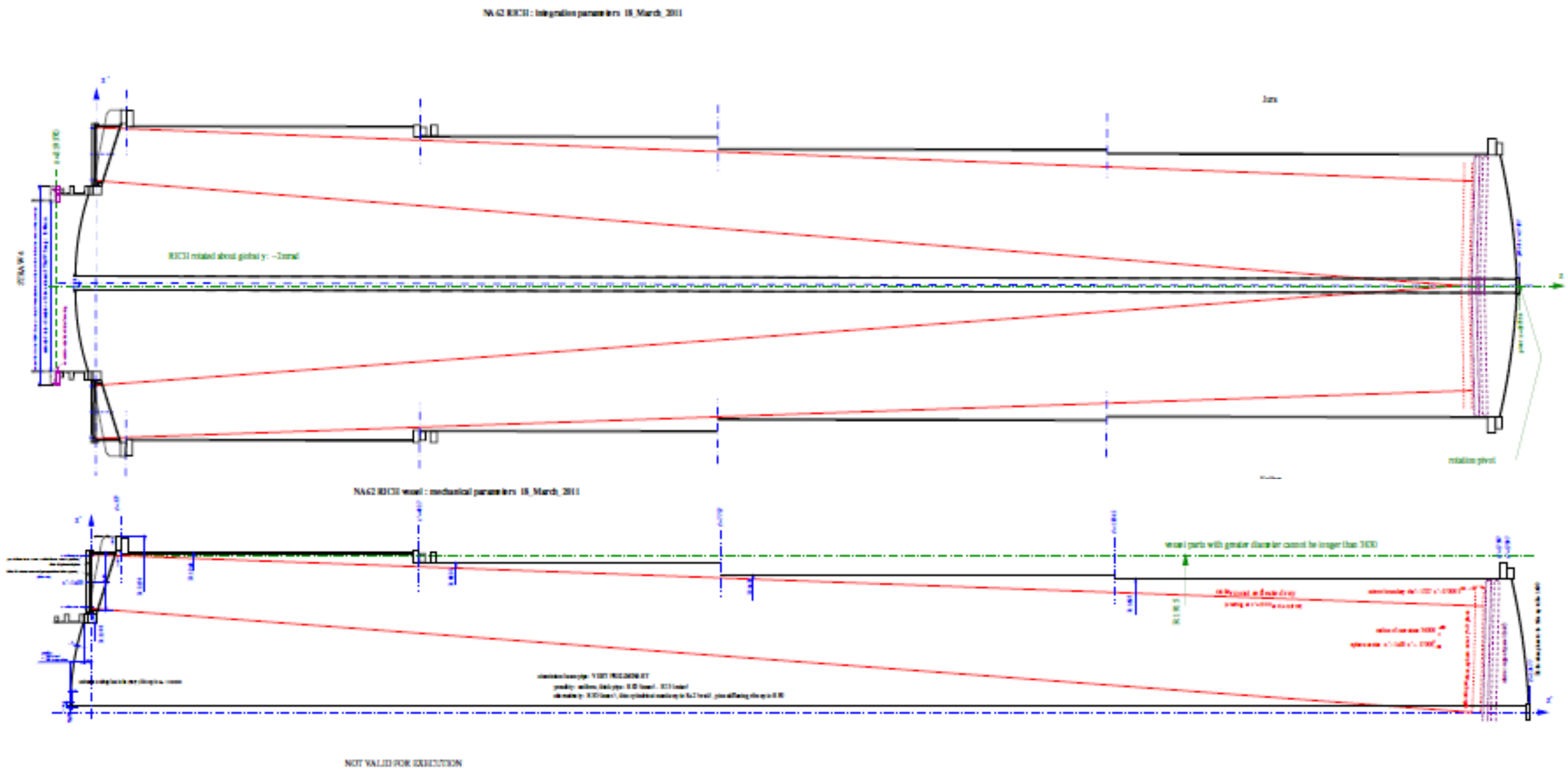




- Ne @ 1 atm ($\approx 5\% X_0$)
- Vacuum proof vessel
- 20 mirror segments ($\approx 20\% X_0$)
- $15 < \frac{p_{tr}}{GeV/c} < 35$
- Contamination of $\mu < 1\%$
- Level 0 Trigger
- $\sigma_t < 100ps$

~ 200 m^3 Ne

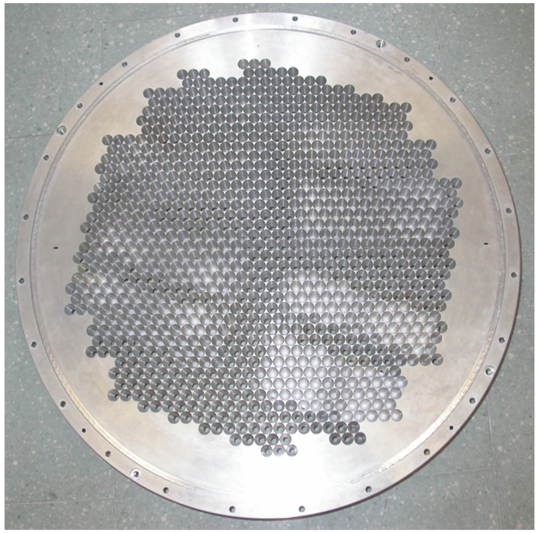
Vacuum proof RICH vessel



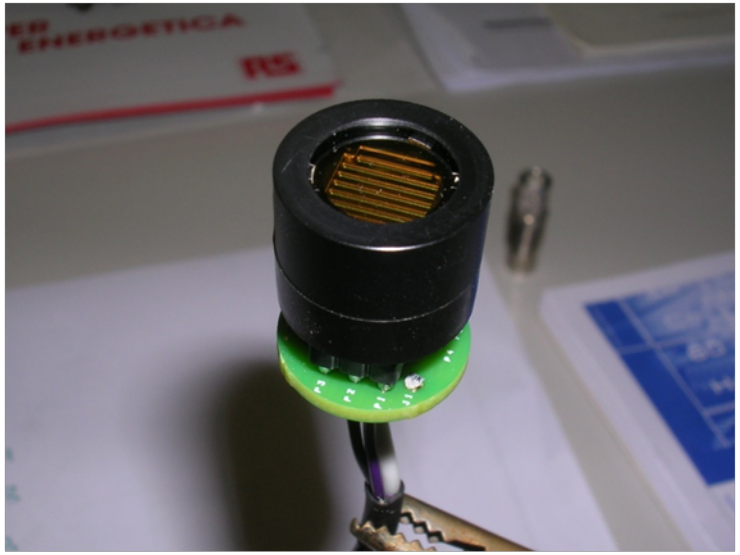
- Simplified gas system: inject pure Neon into an evacuated vessel
- Tender in progress

RICH: Photomultipliers

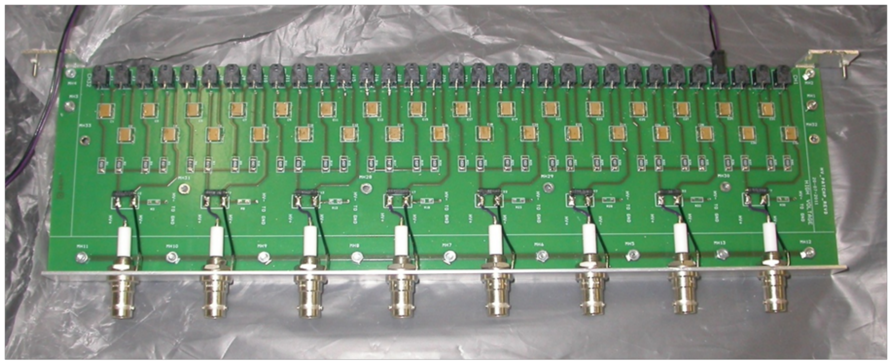
- Hamamatsu R7400 U03 Photomultiplier: >2000 PM already available
- Custom made HV divider to be produced in the coming months



One of the two aluminum disk
separating the Neon gas from the PMs



A PM (Hamamatsu R7400-U03) with
a prototype HV-divider without the insulating case.



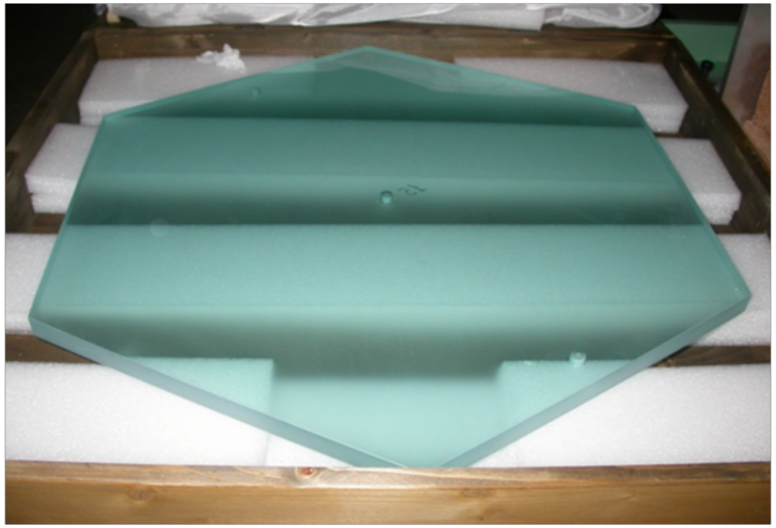
A HV distribution board: for each HV channel
(SHV connectors, at the bottom of the figure)
four PM are supplied (small black connectors at
the top); each board supplies 32 PMs.

RICH: mirrors

- All mirrors at CERN (18 hex + 2 semi-hex)
- Coating to be done at CERN
- Optical quality tests already done

Mirror support system with a “dummy” mirror:
- hung at the center
- aligned with micrometric piezo.motors

One of the hexagonal mirrors before aluminization



One of the semi-hexagonal mirrors before aluminization

NA62: the main detectors

CEDAR: the Kaon Tagger (KTAG) ➔ PID: kaons

- It positively identifies the kaons before they enter the decay region.
- It must tag **~50 MHz of Kaons** and be as thin as possible.
- It must time-stamp the K^+ with an RMS of better than 100 ps in order to improve the association of the parent K^+ with the daughter π^+

Gigatracker (GTK) ➔ the beam Tracker

- Silicon Pixel tracker to measure direction and momentum on event-by-event basis.
- The beam rate is almost **1 GHz** (hence the detector name…).
- It must be very thin to avoid too many inelastic interactions…
- Excellent time resolution is required to time stamp each track **(< 200 ps / hit)**

Straw Tracker ➔ the decay charged particles Tracker

- A large acceptance spectrometer to reconstructs the decay charged particles.
- To reduce the multiple scattering, it is housed in the vacuum tank.
- The overall thickness of the 16 tracking views amounts to **less than 1% X_0**

Photon Vetoes + LKr Calorimeter ➔ the photon veto system

- A large system of detectors surrounding the decay tank to suppress the π^0 background by about **8 orders of magnitude** in a wide acceptance range.

RICH ➔ PID: pions, muons, positrons, …

- π/μ identification up to 35 GeV/c is achieved by means of a Ring Imaging Cherenkov Counter.
- It provides the time reference to correlate the pion to the correct incoming kaon track **(≤100 ps)**

Muon Vetoes ➔ PID: muons

- To suppress the muons at the trigger and analysis level.
- They consist of hadron calorimeters made of iron and plastic scintillator and a fast veto plane

NA62: Beam & Detectors

Primary SPS beam: p = 400 GeV/c

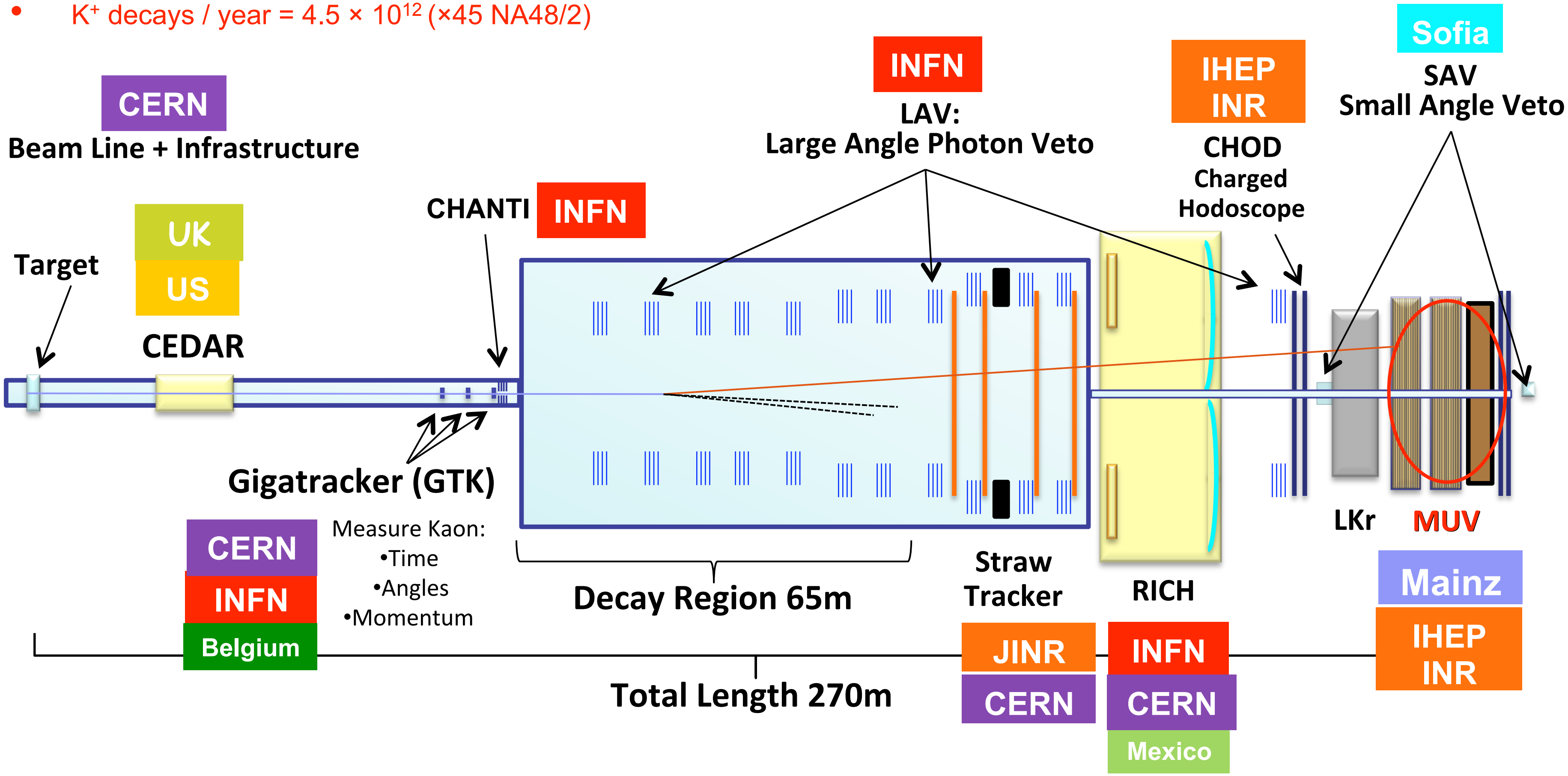
- proton/pulse 3×10^{12} (×3 NA48/2)
- duty cycle 4.8/16.8 s

Secondary unseparated beam:

- p_K = 75 GeV/c (Δp/p~1.1%)
- π/K/p (K^+ ~ 6% , positron free)
- K^+ decays / year = 4.5×10^{12} (×45 NA48/2)

Beam acceptance = 12 mstr (×25 NA48/2)
Area @ beam tracker = 16 cm^2
Integrated average rate = 750 MHz
Average rate @ detectors ≈ 10 MHz

Vacuum at 10^{-6} mbar to reduce beam-gas interaction
(use existing NA48 decay tank)



MUV: the Muon Veto

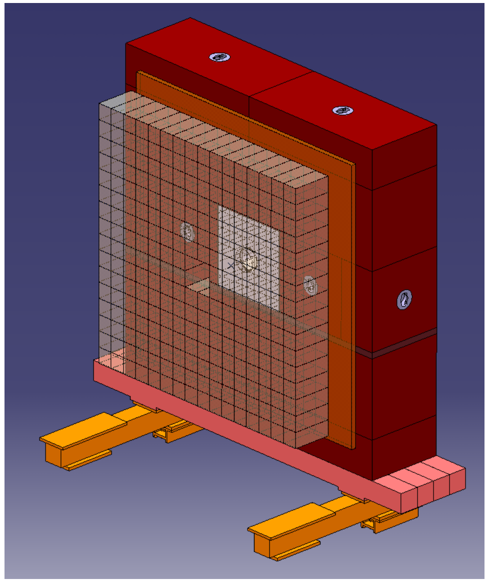
MUV: 3 muon veto stations to reach a factor of 10^6 in muon rejection (combined with the RICH)

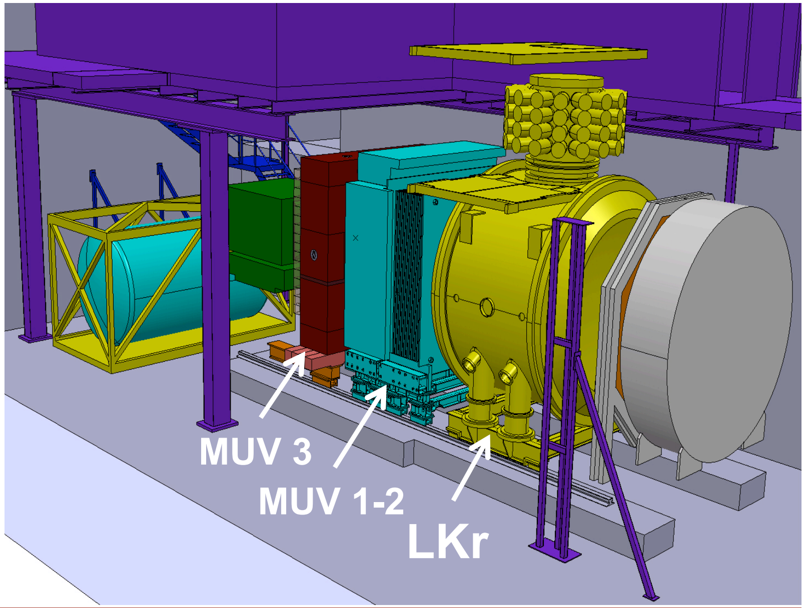
MUV1-2 :

- NA48 Hadron calorimeter partially reused
- 24 (MUV1) and 22 (MUV2) iron/scintillator layers
- alternating horizontal and vertical scintillator strips coupled to PMs

MUV3:

- fast muon identification plane for trigger (L0)
- after 80 cm of iron, 5 cm thick single layer of scintillator tiles readout with 2 PMs
- < 1ns time resolution (test beam result)
- crucial to cope with 10 MHz integrated rate





Present status

- MUV1 construction completed in 2012
- MUV2 reinstallation and commissioning done for participation in technical runs
- MUV3 assembled and tested with cosmics, installation and commissioning planned for participation in technical runs

NA62: Beam & Detectors

Primary SPS beam: p = 400 GeV/c
- proton/pulse 3×10^{12} (×3 NA48/2)
- duty cycle 4.8/16.8 s

Secondary unseparated beam:
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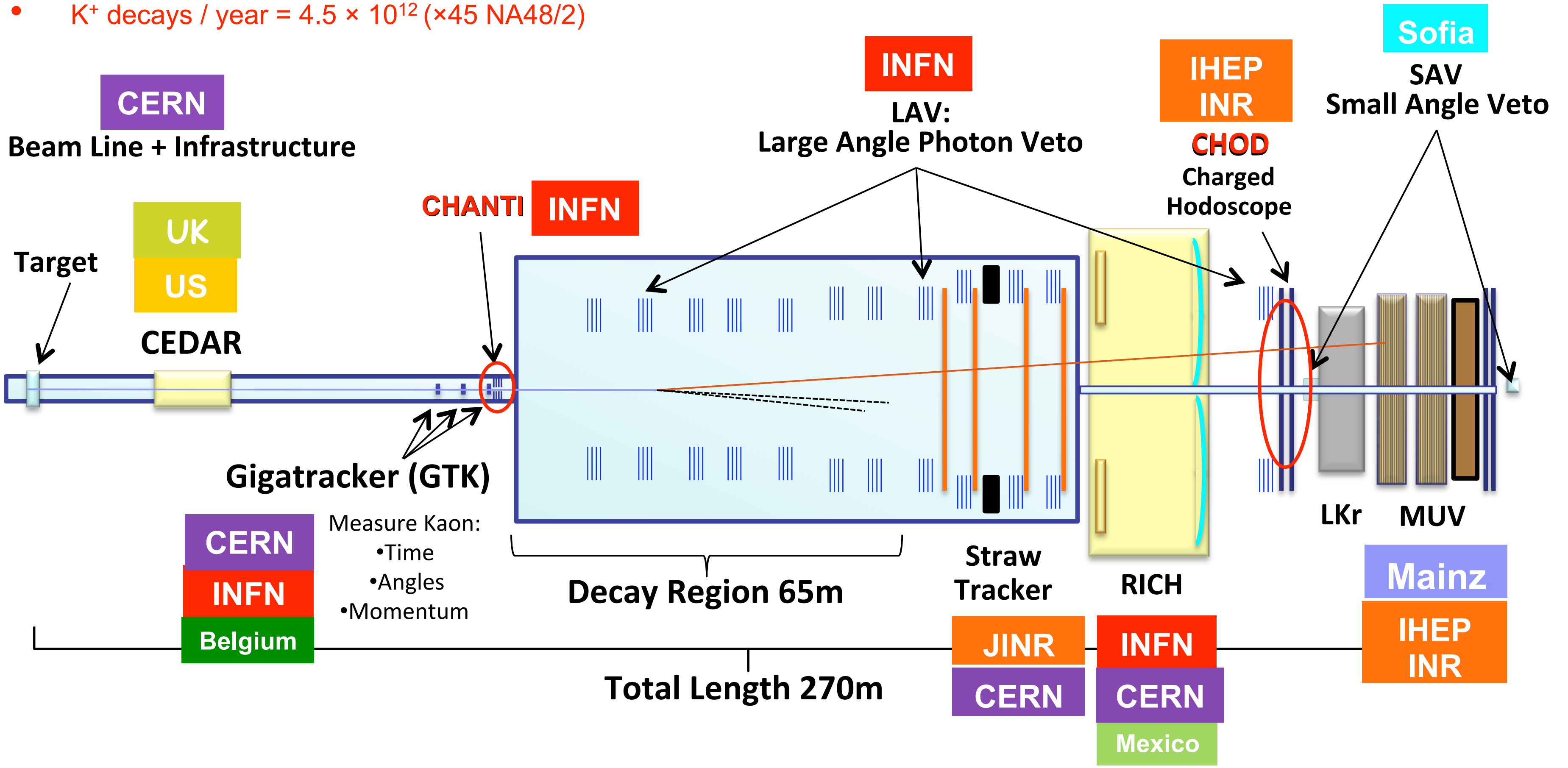
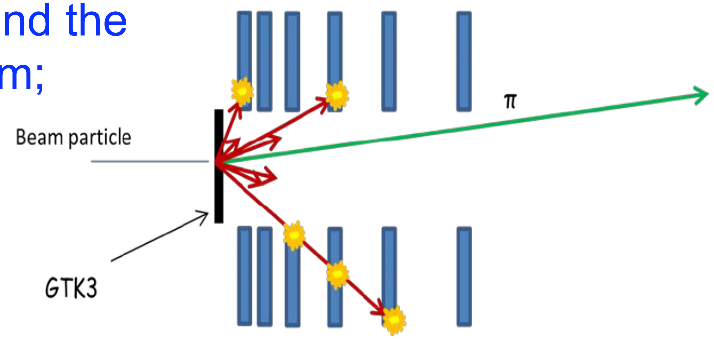


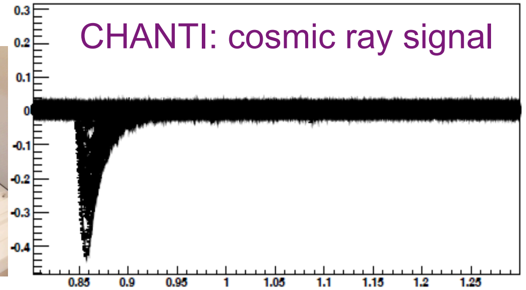
CHANTI and CHOD (Charged Hodoscope)

CHANTI and CHOD: complement tracks detection ➔ veto for charged particles

CHANTI: identify inelastic interactions in the collimator and the GTK by detecting particles at higher angles w.r.t. the beam; identify beam halo μ in the region closest to the beam



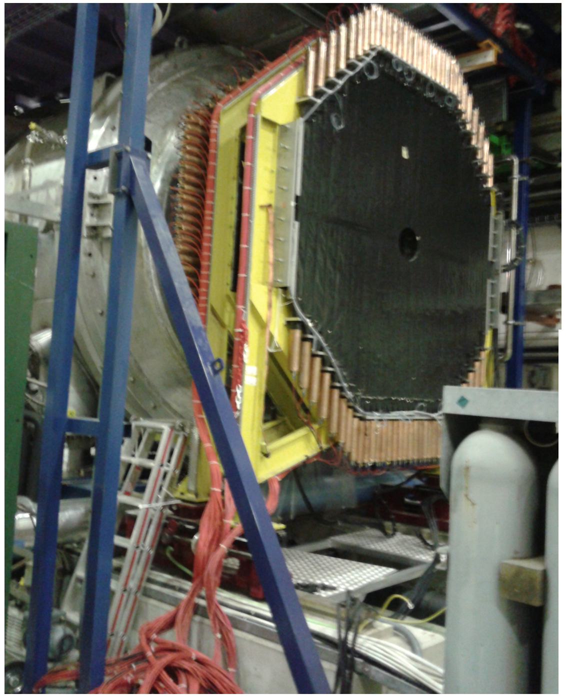
- ➔ guard counters placed right immediately after GTK3
- ➔ 6 stations, 2 layers/station:
  - 22 triangular scintillator bars/layer read out by SiPM
  - first station completed, second station bars test started

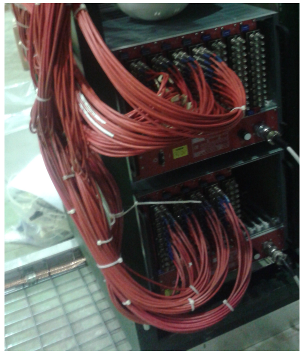


CHOD: trigger decays with charged particle final states and veto multiple charged particle events:

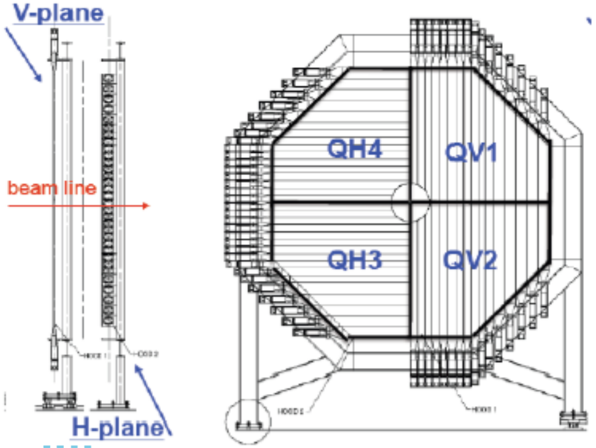
- ➔ stand a rate of about 11 MHz
- ➔ provide a fast L0 trigger signal
- ➔ provide fast timing capability also at the online level: accuracy < 1 ns
  - suppress accidental events
  - complement RICH informations in identifying charged tracks (also at L0)
- ➔ effective vetoing of photon conversions or photonuclear interactions producing low energy hadrons in the detector material
  - complement the LKr photon detection capability at low energy (also at L0)
- ➔ acceptance adequate to complement MUV and RICH detectors in identifying μ at L0 trigger
- ➔ use NA48 CHOD in 2012; prototype of new detector based on scintillator pads and SiPM

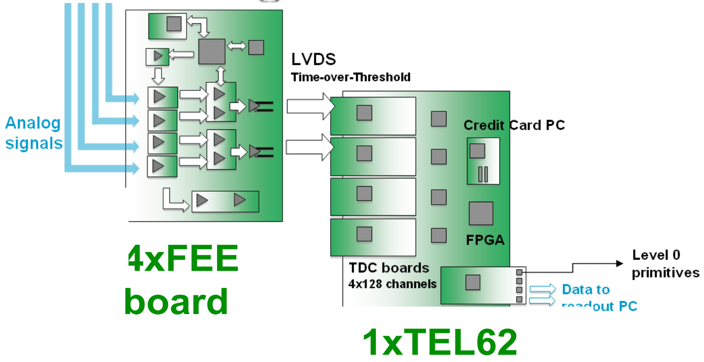
CHOD on 2012 run





Refurbished NA48 CHOD
New HV system (RICH)
New F/E, R/O, Pretrigger



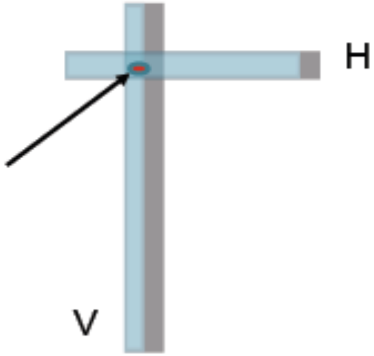


Re-use the NA48 CHOD in 2012:

- *all PMs are working (HV from RICH)*

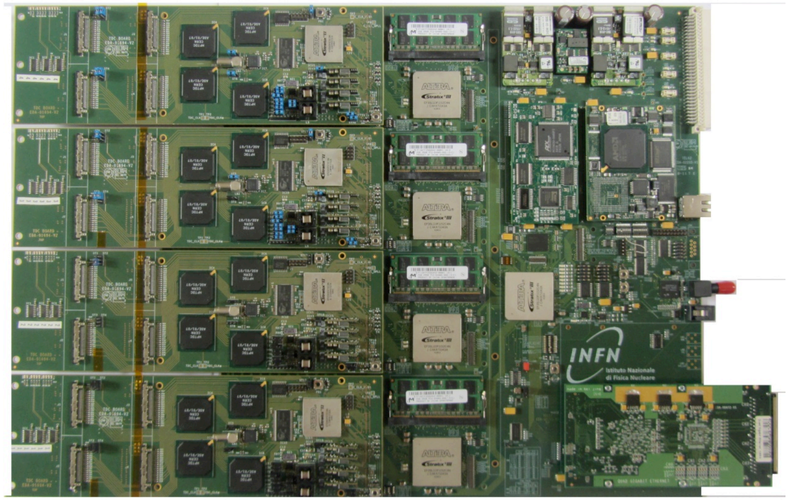
Use the standard NA62 TDAQ from other detectors:

- *Front-end electronics from LAV*
- *Readout based on TEL62/TDCB*
  - *borrow electronics crate and modules from RICH*
  - *new pretrigger logic firmware developed on the TEL62/TDCB FPGA's*



NA62 readout: TEL62

- The TEL62 is a main board to digitize (using daughter boards) buffer data and to build trigger primitives. It's an evolution of the LHCb TELL1 board.
- A board (TDCB) equipped with 128 ch. of TDC (HPTDC, 100 ps LSB) has been developed.
- One TEL62 mother board houses 4 TDCB (512 ch.).
- The trigger primitives are built in parallel with the readout on the same TEL62 board (implemented in firmware using the board's FPGA's)
- Technical run 2012: 13 TEL62 boards will be available, with special crates



Detector	TEL62 (2012)
CEDAR	1
CHANTI	1
LAV	3
STRAW	1
CHOD	1
LKR/L0	3
MUV2	1
MUV3	1
SAC/IRC	1

Trigger and Data Acquisition

Requirements:

- Reduce online 10 MHz rate/detector to 10 kHz
- High data bandwidth
- No zero suppression (for candidate events)
- Very good online time resolution (< 1 ns) to avoid random veto (< 1%)

Solution:

- Integrated system Trigger + DAQ
- Completely digital data stream from FE to TDAQ
- Fully monitored system
- Uniformity for most subdetectors
- Custom hardware minimized
- L0 hardware, L1/L2 software
- Flexibility (for additional physics program)

L0: Hardware level

➔ synchronous; decision based on primitives produced in the readout boards of the detectors partecipating to trigger

L1: Software level

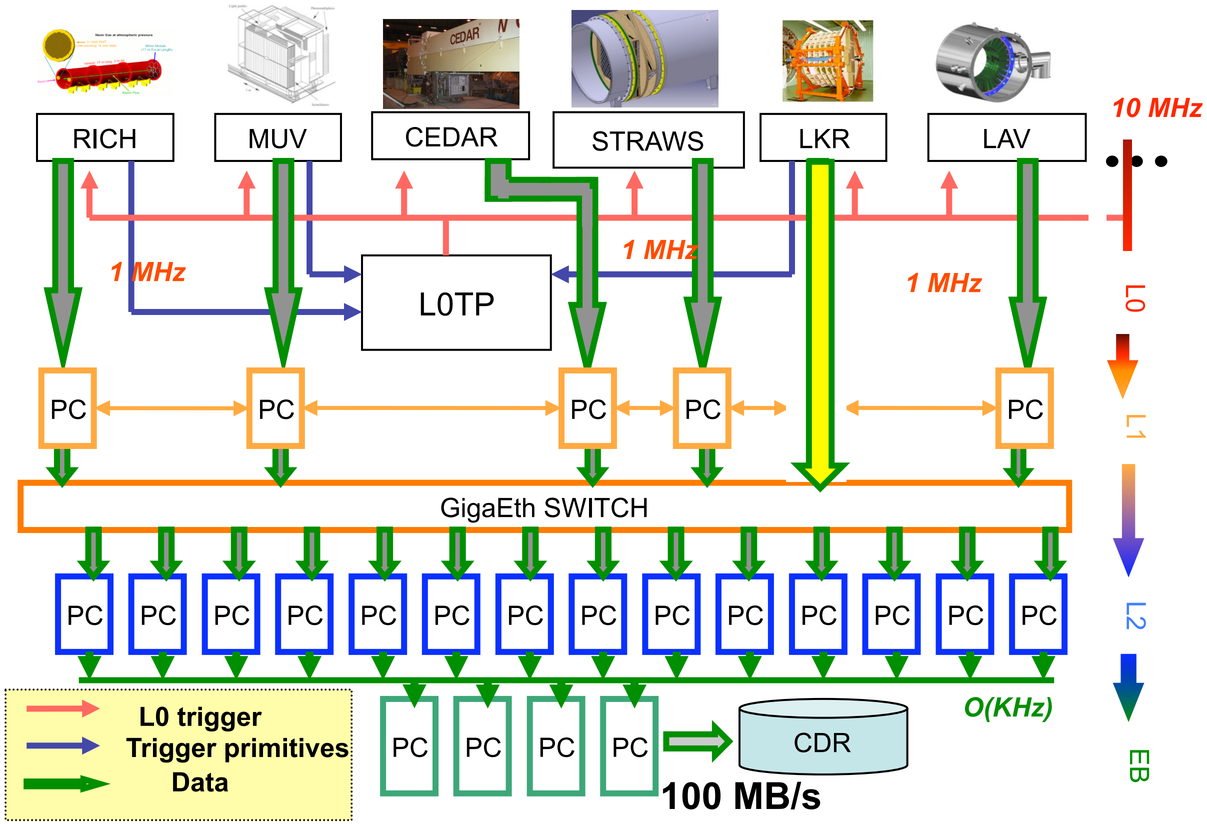
➔ asynchronous (ethernet); "Single detector" PCs

L2: Software level

➔ asynchronous; the informations coming from different detectors are merged together

On-line sub-nanosecond time resolution of Veto detectors and RICH is crucial for high efficiency (>95%)

Trigger/Daq General Overview

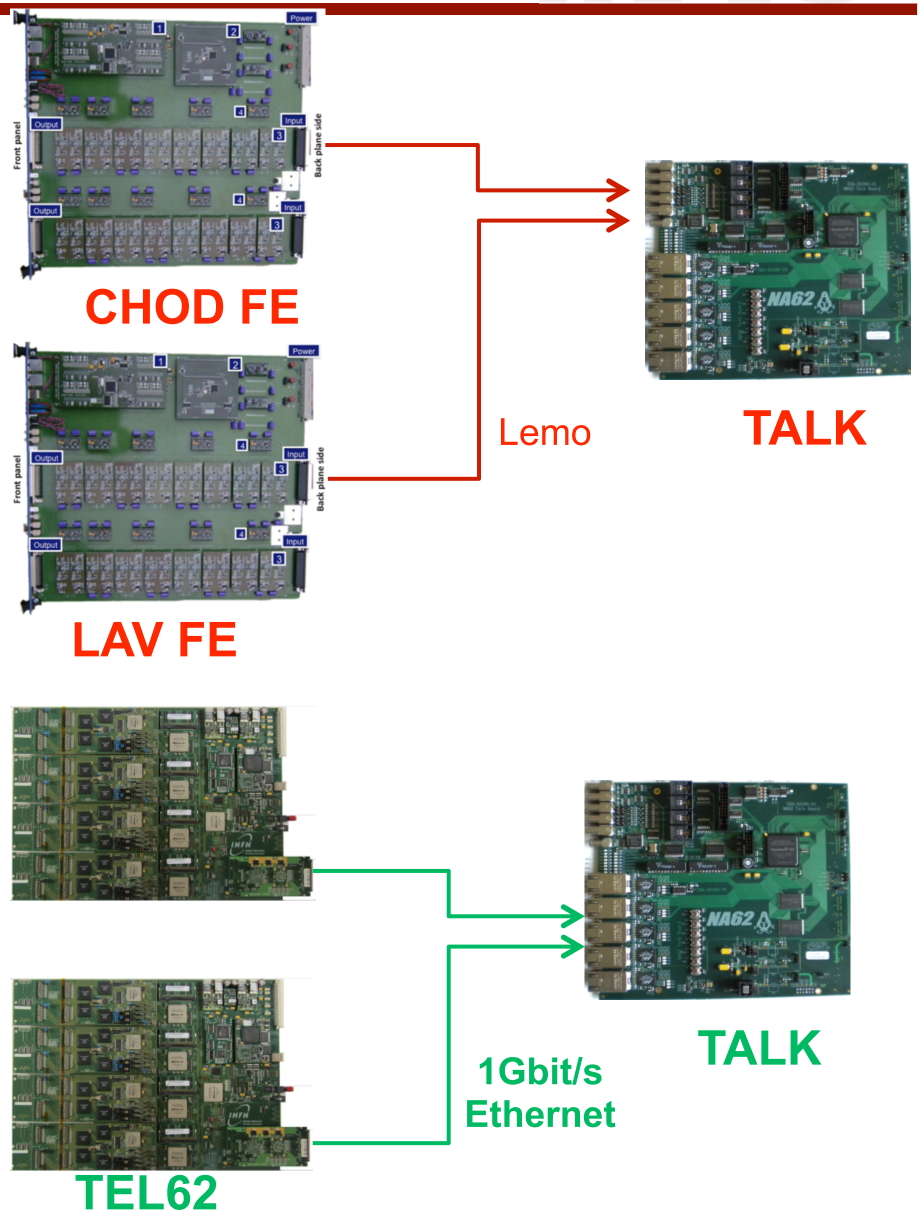


Detector	Rate (MHz)
CEDAR	50
GTK	800
LAV (total)	9.5
STRAW (each)	8
RICH	8.6
LKR	10.5
MUV	9.2
SAC	1.5

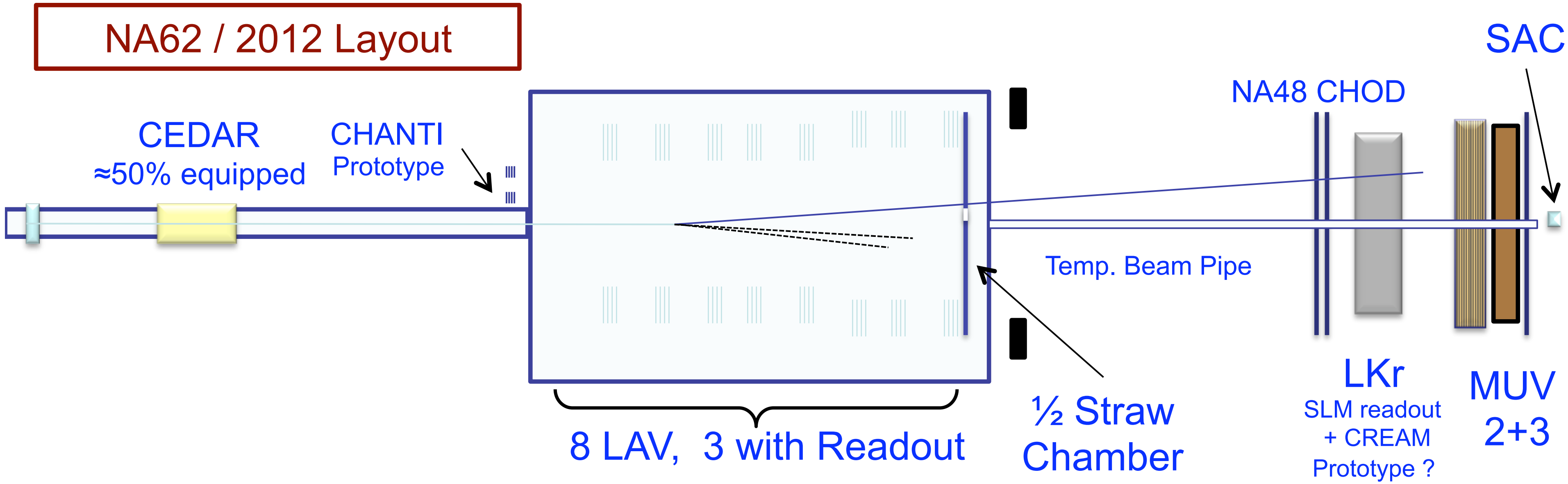
		Input rate (max)	Output rate (max)	latency
L0	hw,syncr.	~10 MHz	~ 1 MHz	1 ms
L1	soft,async.	~ 1 MHz	~ 100 kHz	O(s)
L2	soft,asyncr.	~ 100 kHz	O(kHz)	undefined

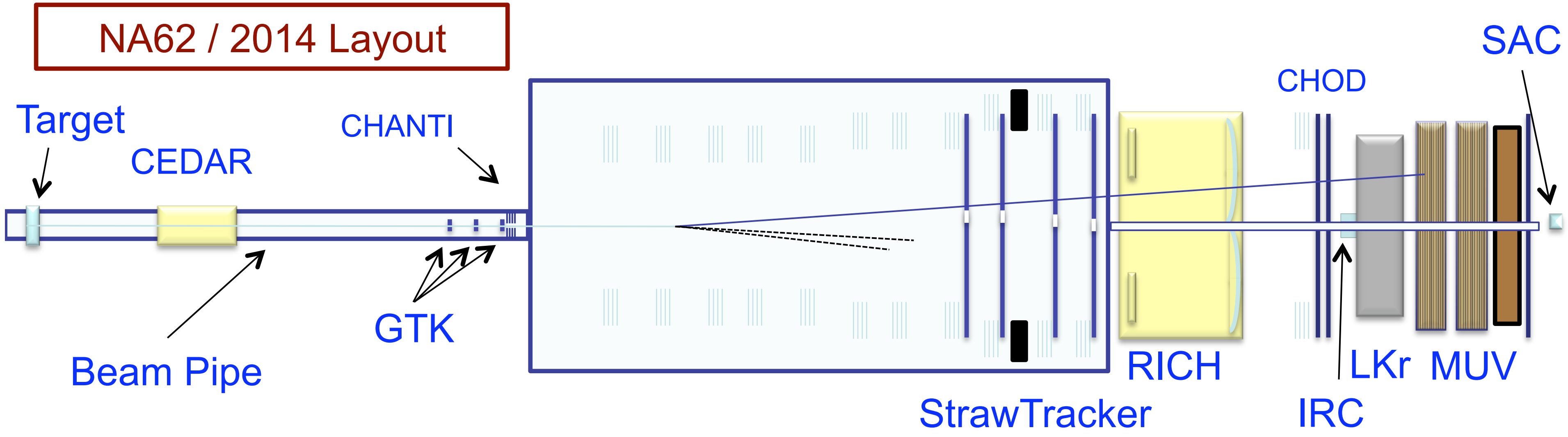
Trigger for 2012 run

- Two ways:
  - With LEMO.
  - Using the primitives produced inside the TEL62.
- The use of asynchronous primitives is the baseline solution. This depends on the specific firmware inside the TEL62.
- The fall back solution will be done using the signals coming directly from the FEE boards.



Commissioning run in 2012





Final $R_K = K_{e2}/K_{\mu 2}$ measurement

The ratio R_K

Very accurate Standard Model prediction of R_k (as well as R_π): theoretical uncertainties on individual decay rates due to hadronic contributions cancel in the ratio

$$R_K = \frac{\Gamma\left(K^\pm \to e^\pm \nu_e\right)}{\Gamma\left(K^\pm \to \mu^\pm \nu_\mu\right)} = \frac{m_e^2}{m_\mu^2}\left(\frac{m_K^2 - m_e^2}{m_K^2 - m_\mu^2}\right)^2 \left(1 + \delta R_{QED}\right) = \left(2.477 \pm 0.001\right) \times 10^{-5}$$

Helicity suppression

Radiative corrections

ChPT, $O(e^2p^4)$

[V. Cirigliano and I Rosell, PRL 99, 231801 (2007), JHEP 0710, 005 (2007)]

➡ Sub-permille (0.04%) accuracy of the SM prediction of R_K

Helicity suppression of R_K might enhance the sensitivity to non-SM effects to a level experimentally accessible

A precise measurement of R_K probes μ–e Universality providing a powerful test of SM

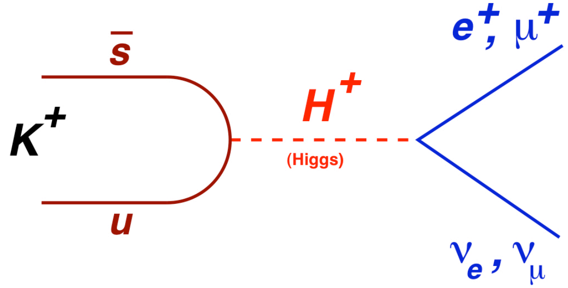
R_K beyond the SM: SUSY

SUSY (MSSM framework) produces sizeable effects to R_K**(SM)**

➔ R-parity is the source of Lepton Universality violating effects

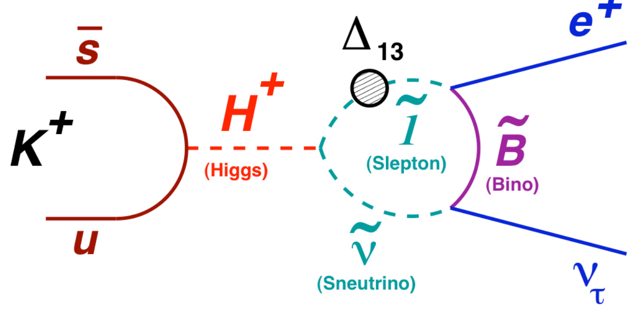
➔ 2 Higgs Doublets Model (A. Masiero, P. Paradisi, R. Petronzio, PRD74 (2006) 011701, JHEP 0811 (2008) 042)

2HDM – tree level: K_{l2} proceeds via exchange of sizeable charged Higgs $H^\pm$ instead of $W^\pm$



2HDM – one-loop level: $H^\pm$ mediated LFV terms with emission of ν_τ are the dominant contribution to ΔR_K

$$R_K^{LFV} \approx R_K^{SM}\left[1+\left(\frac{m_K^4}{m_{H^\pm}^4}\right)\left(\frac{m_\tau^2}{m_e^2}\right)|\Delta_{13}|^2\tan^6\beta\right]$$



Δ_{13} ➔ mixing parameter of superpartners of right-handed leptons

➔ LFV term connected to Helicity suppression in K_{e2}

$\tan\beta$ ➔ ratio of the two Higgs vacuum expectation values

At large $\tan\beta$ values with a massive $H^\pm$, LFV contributions dominate and produce sizable (O(1%)) effects to R_K

(Ex.: $\Delta_{31}=5\times10^{-4}$, $\tan\beta=40$ and $M_H=500$ GeV/c^2 ➔ $R_K^{LFV} = R_K^{SM}(1+0.013)$)

Experimental Status of R_K

PDG'08 (1970s measurements):

$R_K=(2.45\pm0.11)\times10^{-5}$ ($\delta R_K/R_K=4.5\%$)

Most recent measurements:

2009: KLOE (LNF), 2001–05 data (final), 13.8K K_{e2} candidates, 15% background:

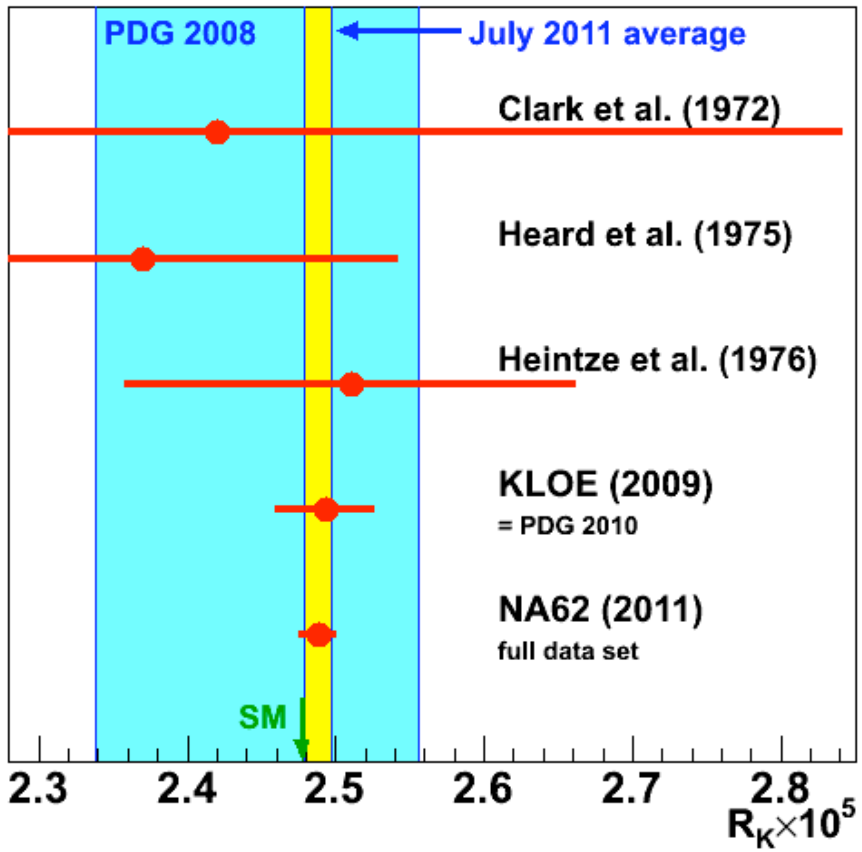
$R_K=(2.493\pm0.031)\times10^{-5}$ ($\delta R_K/R_K=1.2\%$)

(EPJ C64 (2009) 627)

2011: NA62 (CERN), 40% of 2007 data, ≈60K K_{e2} candidates, ≈9% background

$R_K=(2.487 \pm 0.013)\times10^{-5}$ ($\delta R_K/R_K=0.5\%$).

(Phys.Lett. B698 (2011) 105)



Now: **NA62 final result**

full data set: ≈146K K_{e2} candidates ➔ $\delta R_K/R_K=0.4\%$

Analysis strategy

Count reconstructed $K_{e2}/K_{\mu 2}$ candidates collected concurrently

- ➔ Fluxes cancel in the ratio: analysis does not rely on absolute K flux measurement
- ➔ Several systematic effects cancel at first order in the ratio
  (e.g. reconstruction/trigger efficiencies, time-dependent effects, beam simulation)

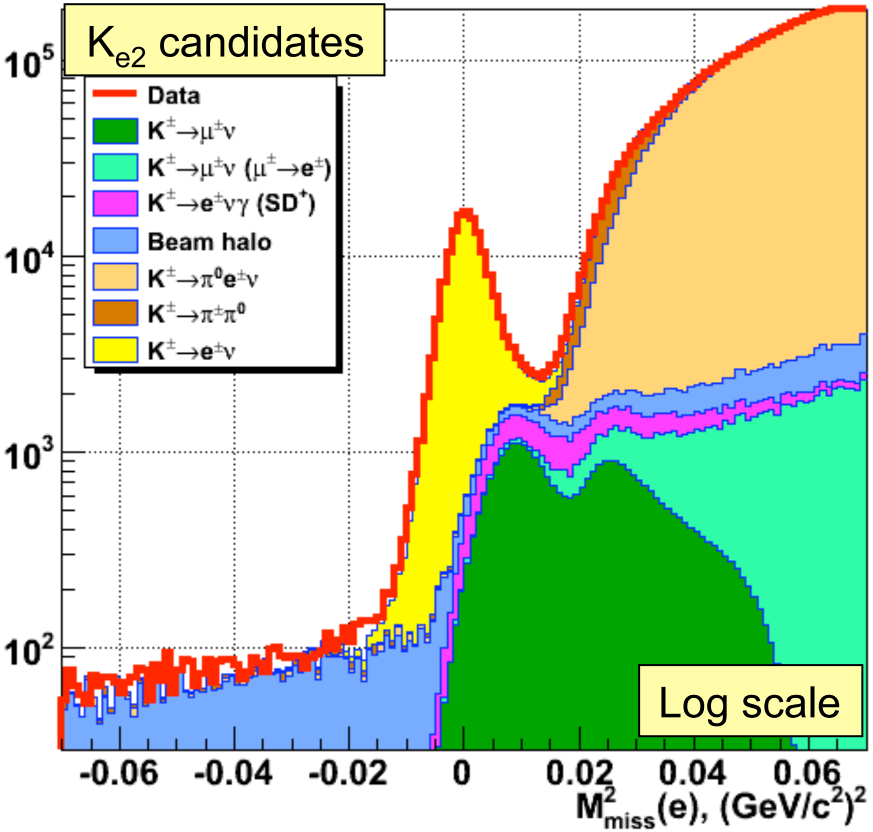
$$R_K = \frac{1}{D} \cdot \frac{N(K_{e2}) - N_B(K_{e2})}{N(K_{\mu 2}) - N_B(K_{\mu 2})} \cdot \frac{A(K_{\mu 2}) \times f_\mu \times \varepsilon(K_{\mu 2})}{A(K_{e2}) \times f_e \times \varepsilon(K_{e2})} \cdot \frac{1}{f_{LKr}}$$

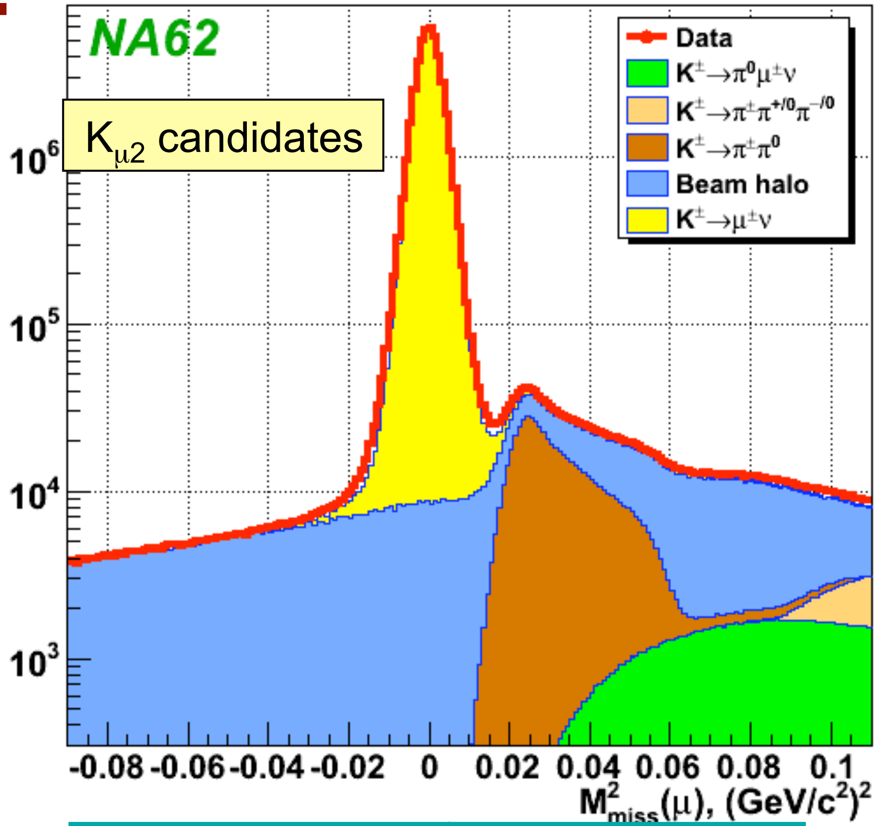
$N(K_{e2})$, $N(K_{\mu 2})$:	numbers of selected K_{l2} candidates
$N_B(K_{e2})$, $N_B(K_{\mu 2})$:	numbers of background events;
$A(K_{e2})$, $A(K_{\mu 2})$:	geometric acceptances (MC, no ID);
f_e, f_μ:	particle ID efficiency (measured, no MC);
$\varepsilon(K_{e2})/\varepsilon(K_{\mu 2})$:	trigger efficiency;
f_{LKr}:	global LKr readout efficiency (only K_{e2});
D:	downscaling factor of the $K_{\mu 2}$ trigger (D=150).

$N_B(K_{e2})$: the **main source of systematic errors** comes from the K_{e2} background subtraction

- ➔ count of events done independently in 10 lepton momentum bins
  (due to strong dependence of backgrounds and acceptance on lepton momentum)
- ➔ MC simulations (Geant3) used for the geometric acceptance correction
- ➔ PID, trigger, readout efficiencies are measured directly from data

K_{e2} and $K_{\mu 2}$ data samples





145.958 $K^\pm \to e^\pm \nu$ candidates

10.95% background

Electron ID efficiency: (99.28±0.05)%

42.817 x 10^6 $K^\pm \to e^\pm \nu$ candidates

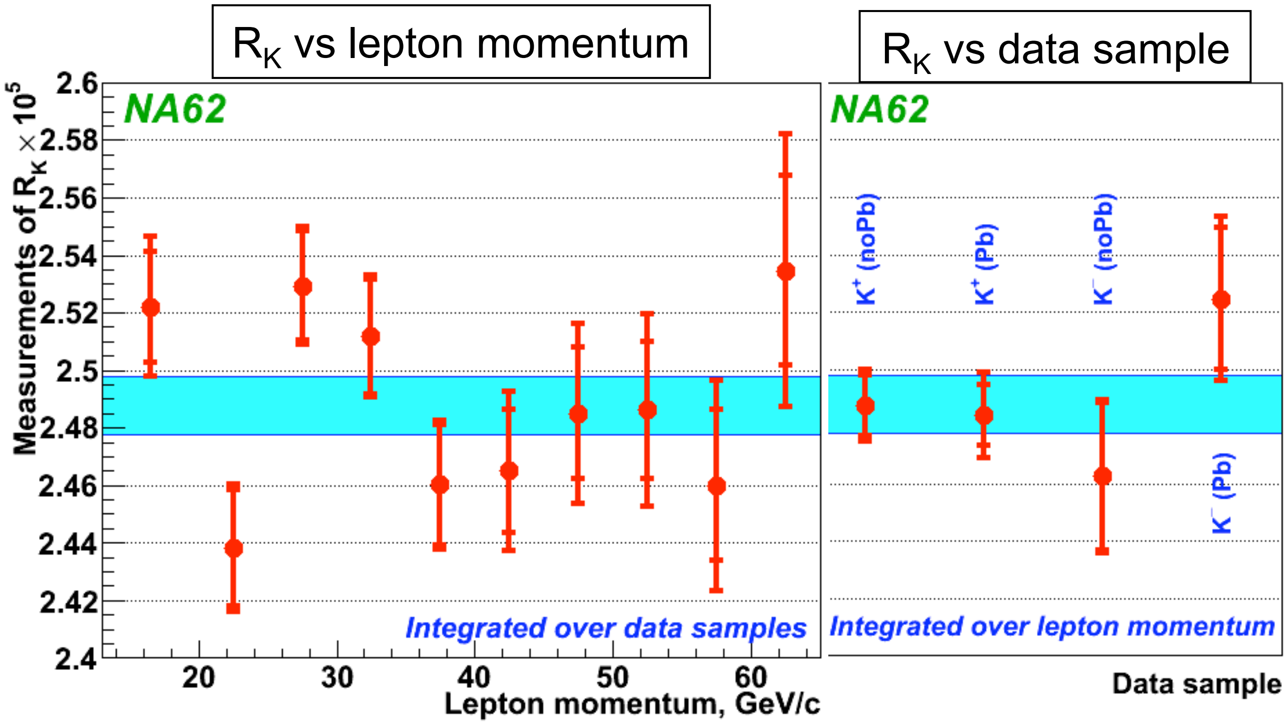
0.50% background

Background source	B/(S+B)
$K_{\mu 2}$	(5.64±0.20)%
$K_{\mu 2}$ ($\mu \to e$)	(0.26±0.03)%
$K_{e2\gamma}$ (SD^+)	(2.60±0.11)%
$K_{e3(D)}$	(0.18±0.09)%
$K_{2\pi(D)}$	(0.12±0.06)%
Wrong sign K	(0.04±0.02)%
Muon halo	(2.11±0.09)%
Total	(10.95±0.27)%

The NA62 final result (full data set)

$$R_K = (2.488 \pm 0.007_{stat} \pm 0.007_{syst}) \times 10^{-5}$$
$$R_K = (2.488 \pm 0.010) \times 10^{-5}$$

Fit over 40 measurements (4 data samples × 10 momentum bins) including correlations: χ^2/ndf=47/39



Uncertainty source	$\delta R_K \times 10^5$
Statistical	0.007
$K_{\mu 2}$ background	0.004
$K^\pm \to e^\pm \nu\gamma$ (SD$^+$)	0.002
$K^\pm \to \pi^0 e^\pm \nu$, $K^\pm \to \pi^\pm \pi^0$	0.003
Beam halo background	0.002
Thickness of spectrom.	0.003
Acceptance correction	0.002
DCH alignment	0.001
Electron identification	0.001
1TRK trigger efficiency	0.001
LKr readout efficiency	0.001
Total uncertainty	0.010

Summary

- The **K** $\rightarrow$ **$\pi\nu\bar{\nu}$** decay: high quality precision physics complementary to the high-energy approach for NP searches
- A challenging experimental program is going on in NA62 at CERN
  - ➜ *Collect 0(100) events in two years to provide a 10% precision on BR($K^+ \rightarrow \pi^+\nu\bar{\nu}$)*
  - ➜ *Key points: high intensity beams, excellent resolutions, hermetic coverage, Particle Identification, redundancy of information*
- Schedule
  - ➜ *Construction in progress*
  - ➜ *Dry and Technical runs in summer/falls 2012*
  - ➜ *Ready to take data after CERN accelerator long shutdown*

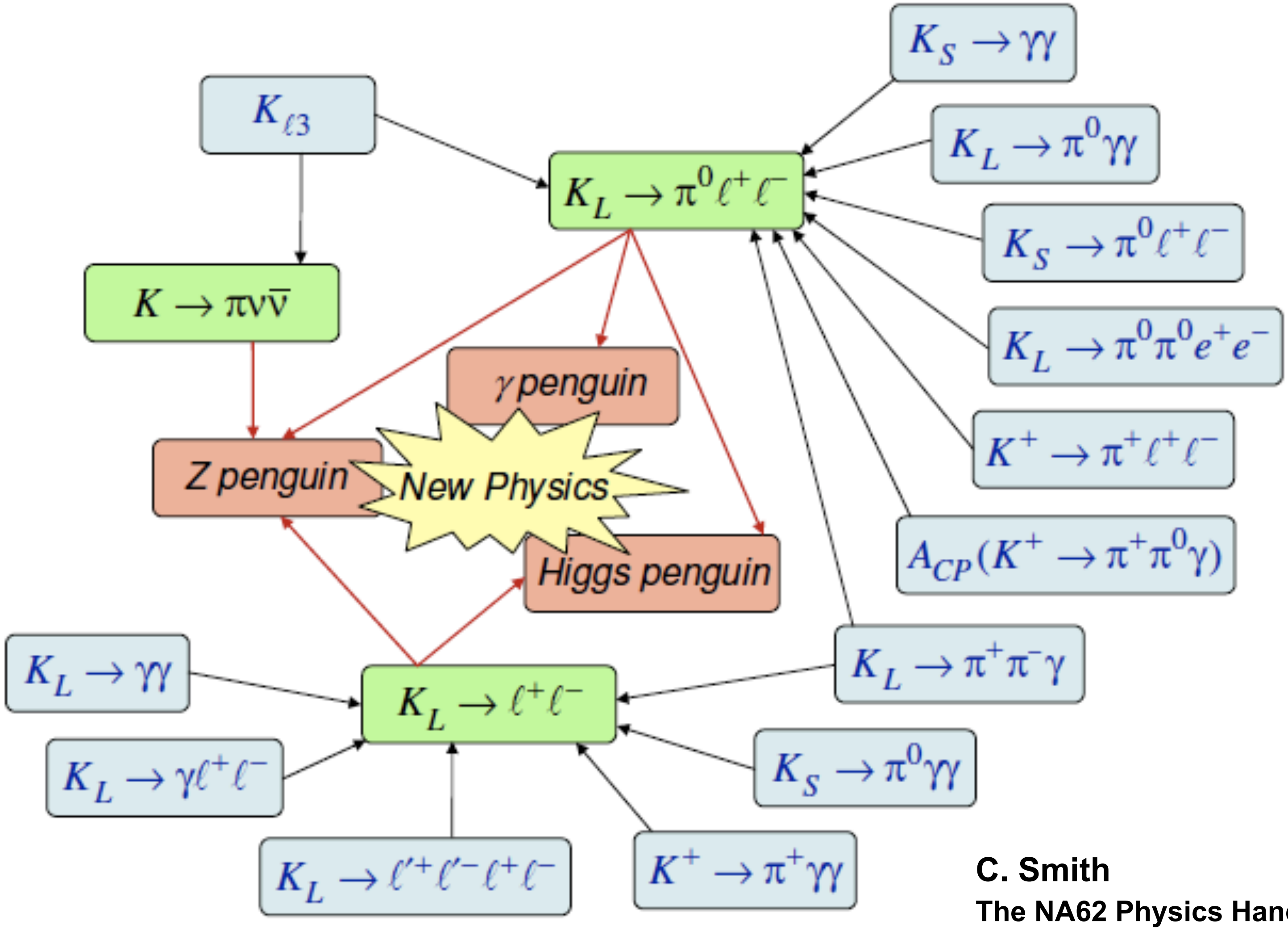

NA62 Penguins at work

- A precision of 0.4% has been achieved on R_K
  - ➜ *Further improvement is expected with the data from the NA62 physics runs*
- The high performances of the detectors can be the building blocks for a further physics program (as in NA48)

A very rich program is expected in the near future

Outlook

Kaon decays: the full picture

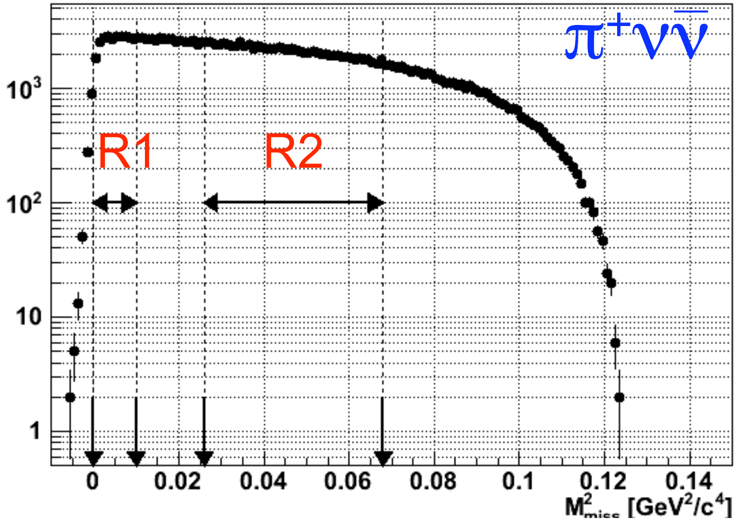


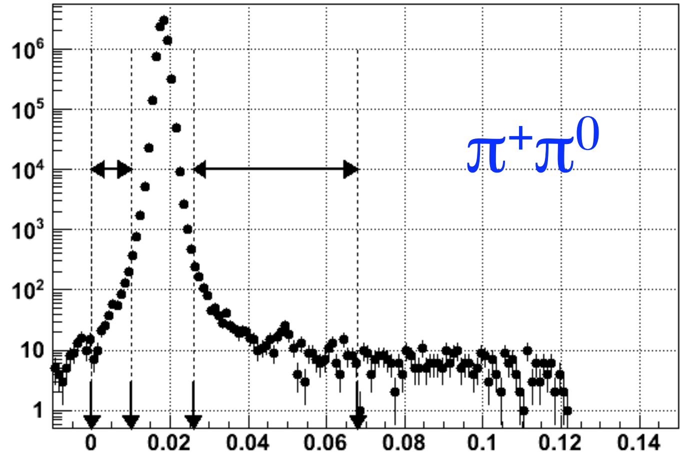
C. Smith
The NA62 Physics Handbook Workshop
CERN, 10-12.12.2009

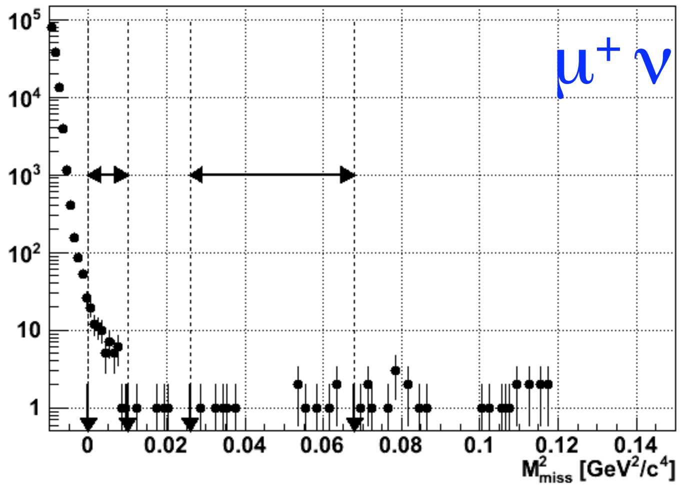
spare

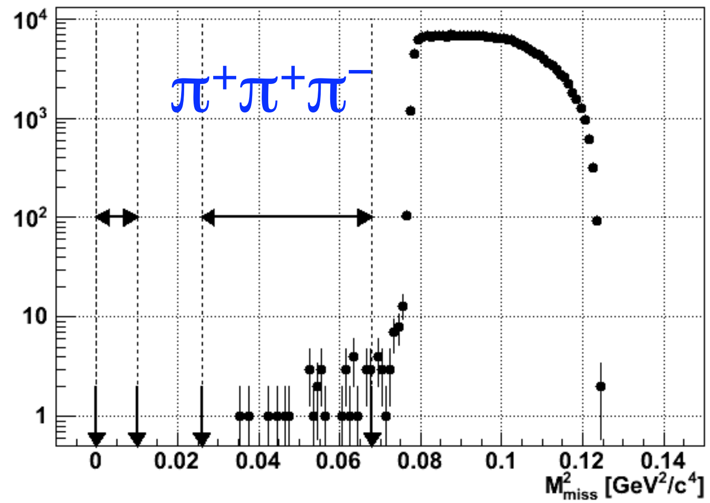
Kinematic Selection: cuts on M^2_{miss}

M^2_{miss} resolution: non-gaussian tails



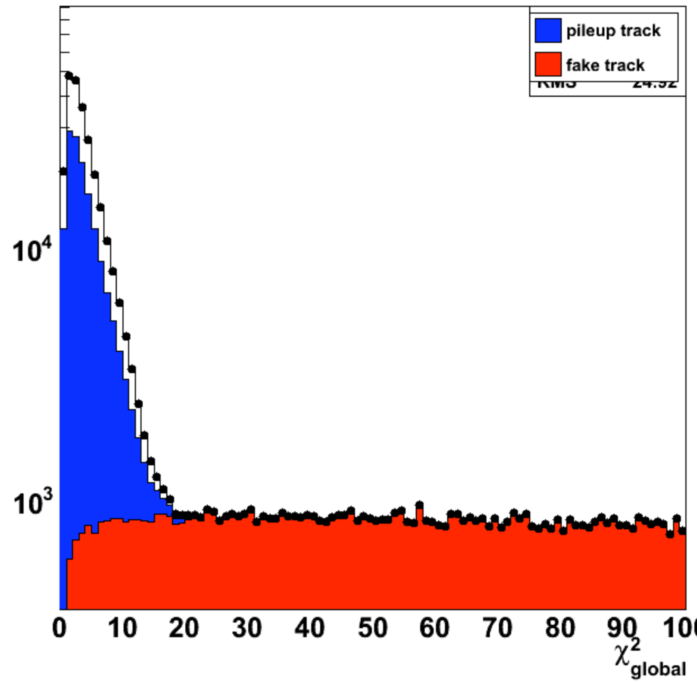






Beam Pileup and GTK reconstruction

- Pileup simulation: Rate=750 MHz in GTK
  - Average tracks in GTK per event: 2.5 (1 K, 1.5 pileup)
- All possible GTK hit combinations considered
  - Real tracks: GTK hits from the same track (Pileup tracks, Kaon tracks).
  - Fake tracks: GTK hits from different beam track
- Before selection cuts:
  - Average reconstructed track per event: 27
  - Fraction of: Kaons 3.6%, Pileup 5.3%, Fake 91%

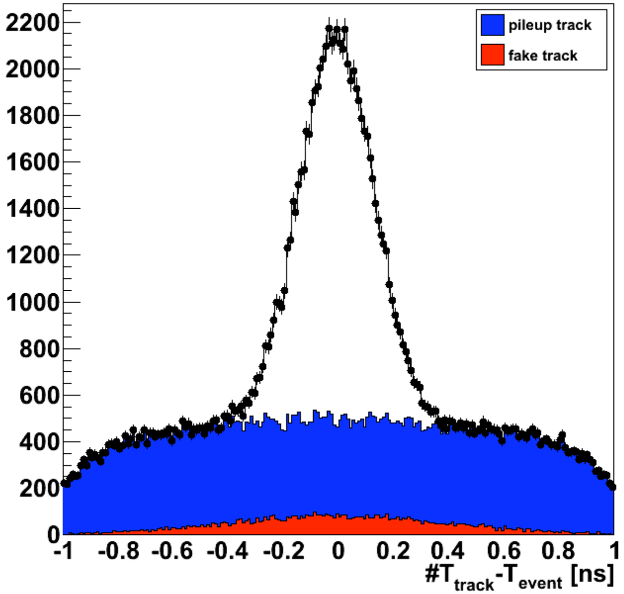


- Real Track Recognition:
- Discriminant variable: global χ^2
- Track recognition: global $\chi^2 < 20$.
- After track recognition:
  - Average reconstructed track per event: 2.6
  - Fraction of: Kaons 38% , Pileup 56%, Fake 6.1%.

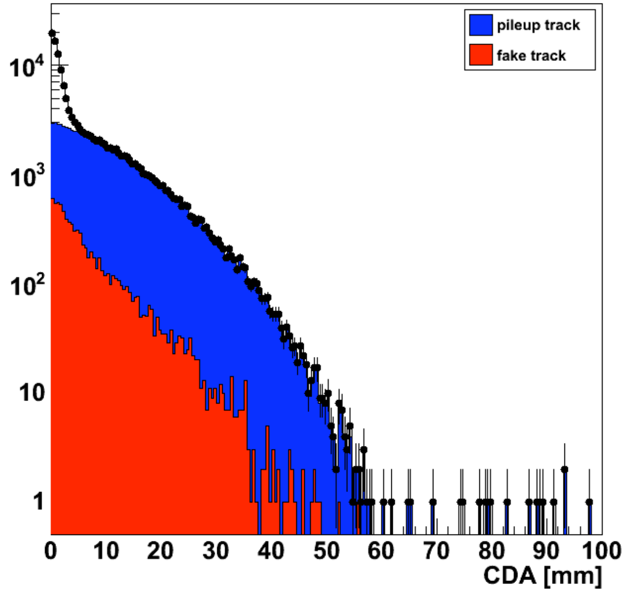
Beam Pileup and Kaon-ID

- Inputs for Kaon track identification: $\Delta T = T_{track} - T_{event}$, CDA.

ΔT for all the tracks



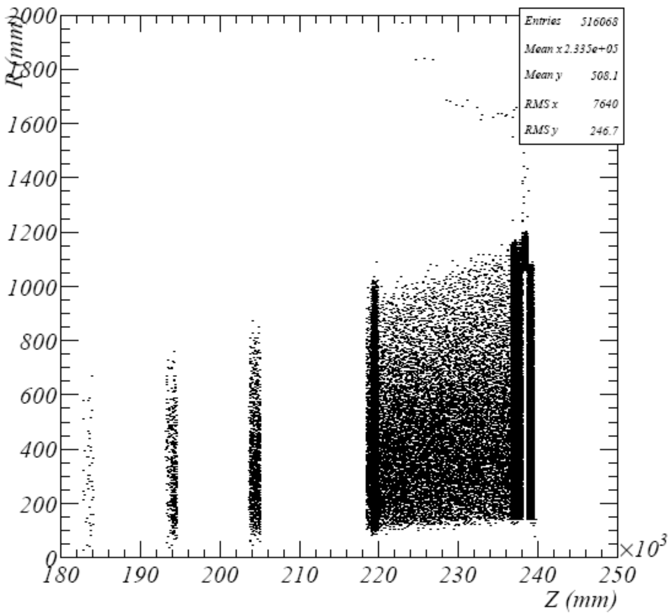
CDA for all the tracks



- Results after Kaon - ID:
- Fraction of: Kaons 99.4%, Pileup 0.6%, Fake <0.1%

Photons in the Forward Region

- Evaluate the effect of the material in front of the LKr on the photon rejection inefficiency (straw chambers and RICH).
- Reminder: the LKr intrinsic inefficiency was evaluated on data (NA48 in 2007) .

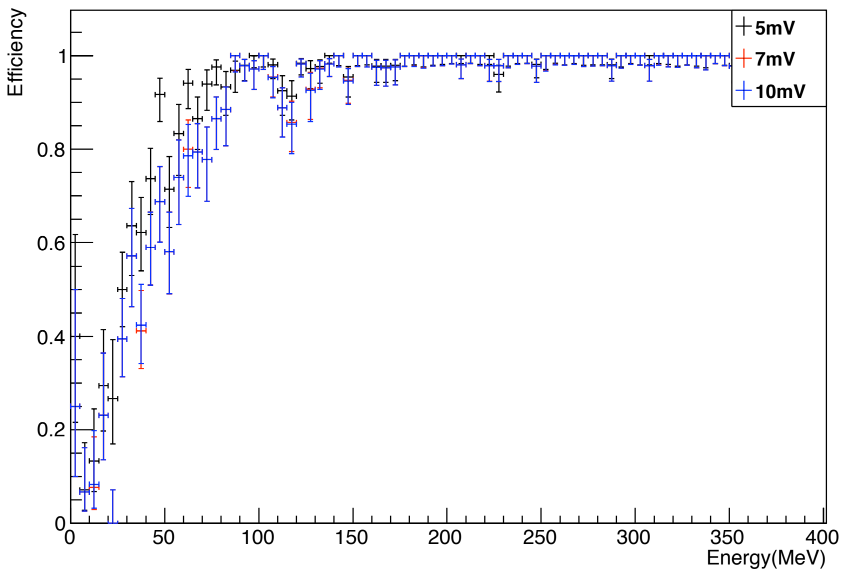


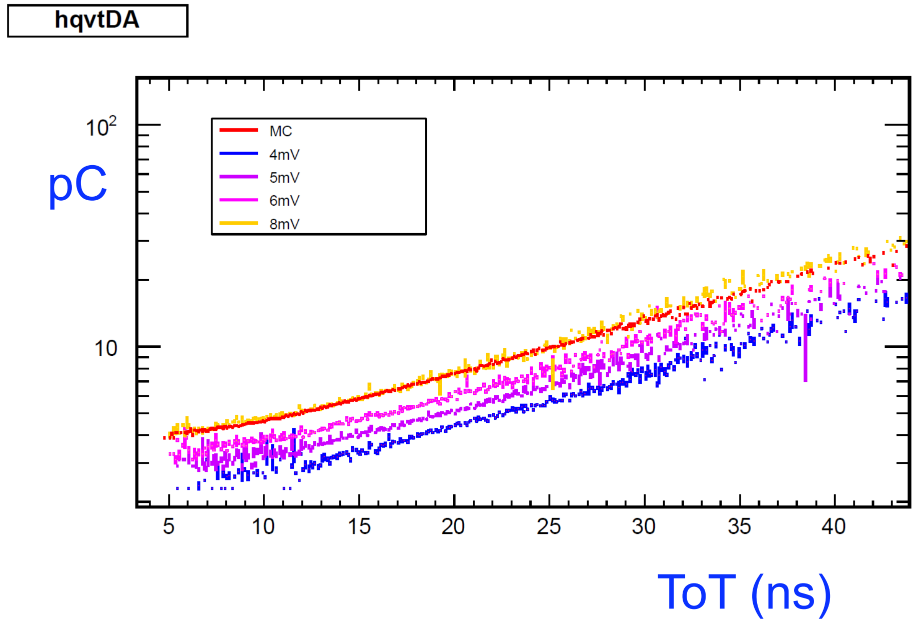
- Probability of γ interaction: 20%
  - Most part of the interactions are simple photon conversions (e^+e^- pairs detected as well in the LKr).
- Probability of γ nuclear interaction: 10^{-3}
- Multiplicity cuts in LAV9,10,11,12 and in the detectors downstream to the RICH applied.

Energy	< 1 GeV	1 – 5.5 GeV	5.5 – 7.5 GeV	7.5 – 10 GeV	>10 GeV
LKr Inefficiency	1	10^{-3}	10^{-4}	5×10^{-5}	8×10^{-6}
Effect of the material	-	$(2.1\pm0.5)\times10^{-4}$	$(1.4\pm0.5)\times10^{-4}$	$(5\pm2)\times10^{-5}$	$(3.7\pm1.6)\times10^{-6}$

LAV simulation

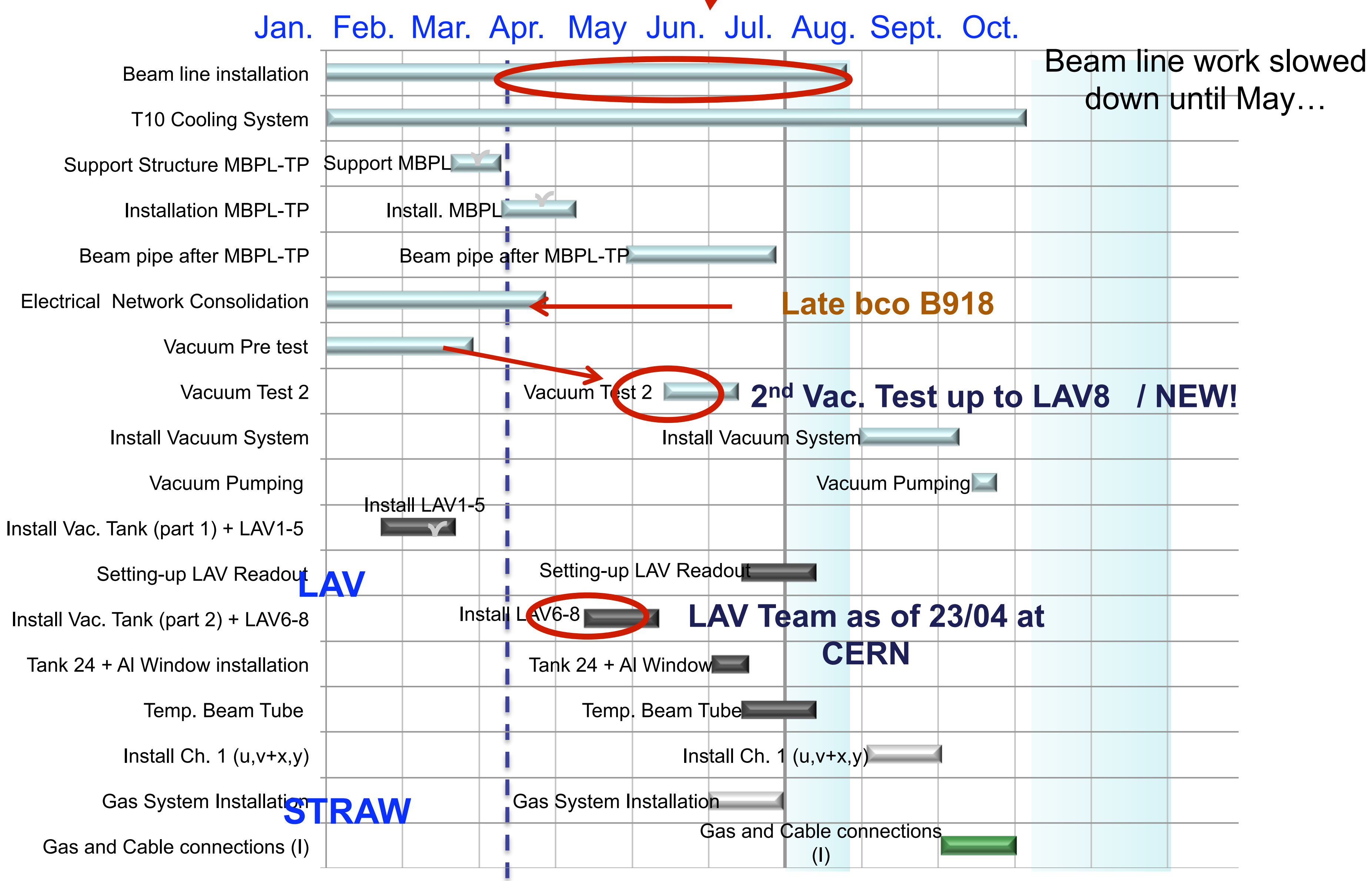
In case of undetected photons by LAV, the other γ from π^0 decay has enough energy to be detected very efficiently by LKr & SAC



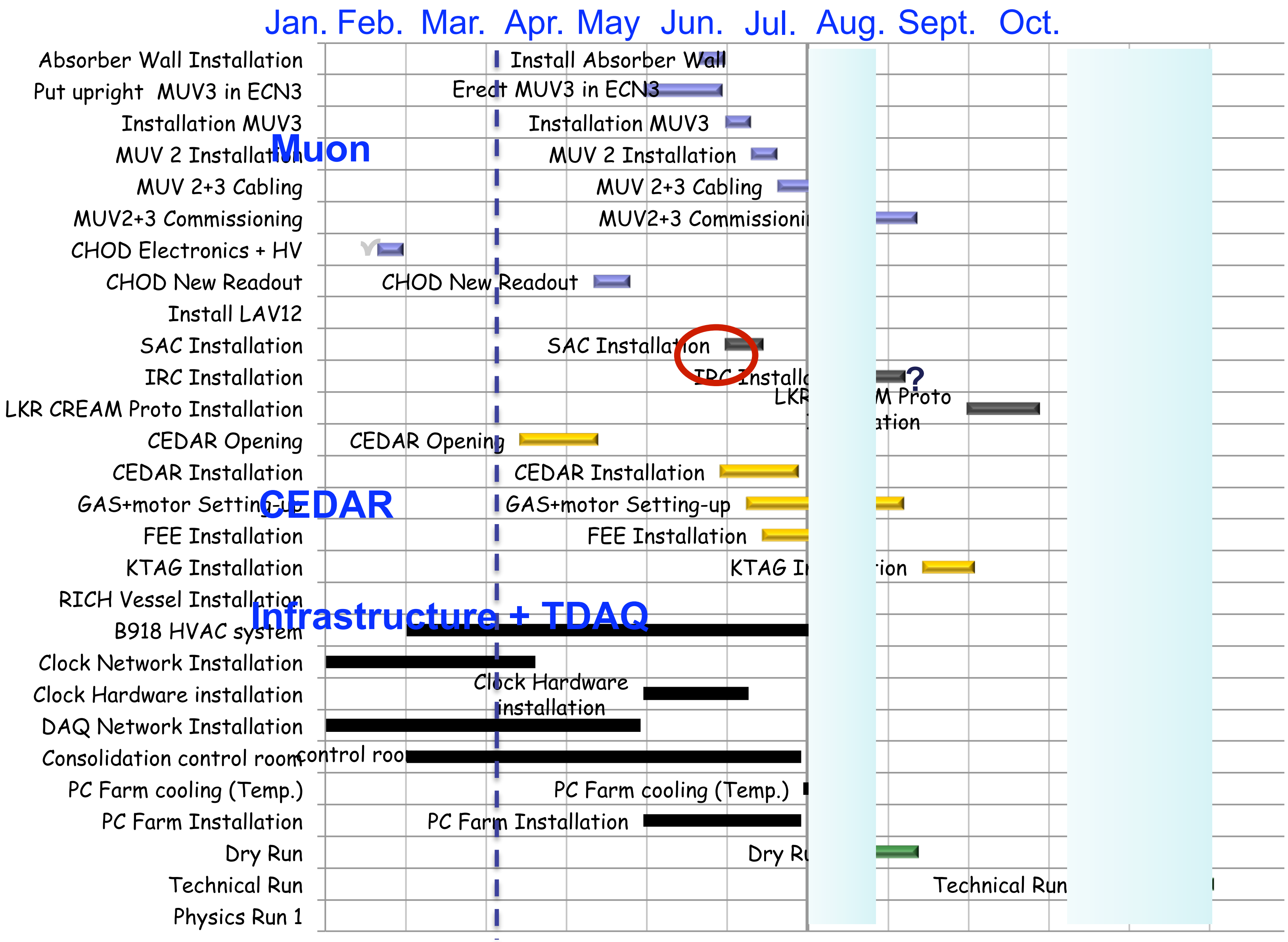


- LAV inefficiency 1-ε ~ 0.3%
- Data-MC Comparison

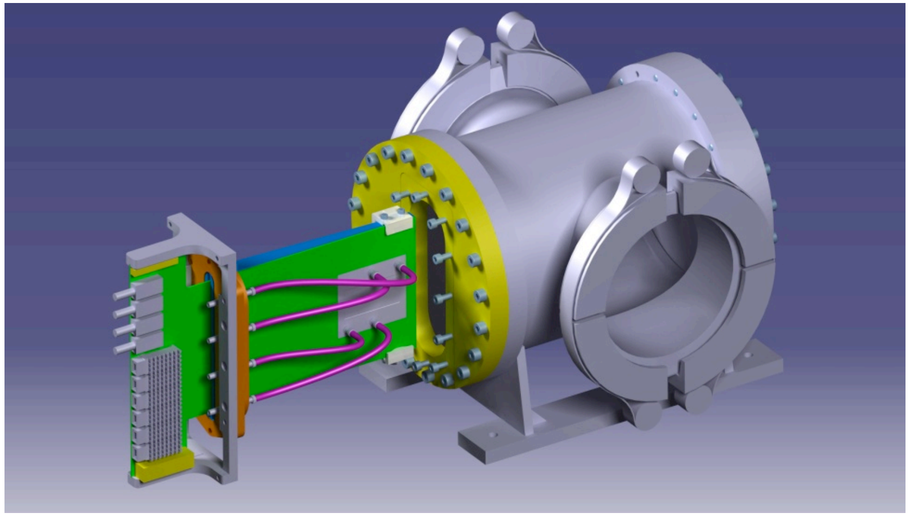
Installation Schedule (2012)



Installation Schedule (2012)



GTK: Mechanics & Read Out



Mechanical Integration

Next steps:

- Mechanical production of GTK1 and GTK2 stations and mounting them on the beamline.
- Finalization of GTK3/CHANTI design and production in the second half of 2012.
- Installation expected for 2013

GTK-RO motherboard prototype

A prototype of the GTK-RO card is under test: basic functionalities have been proven to work.

Next: full production of the GTK-RO modules